Future prospects in the search for *light* hidden particles

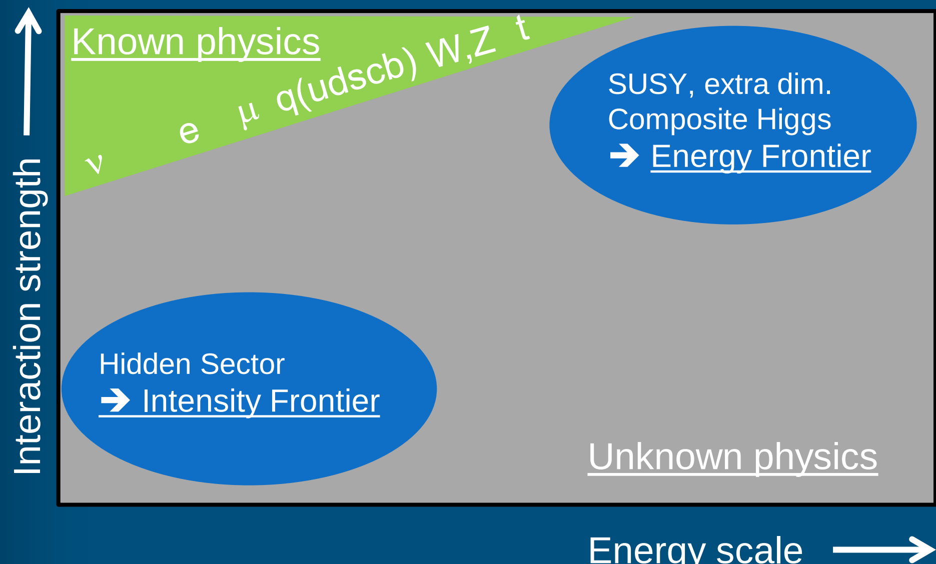
Richard Jacobsson

What if...?

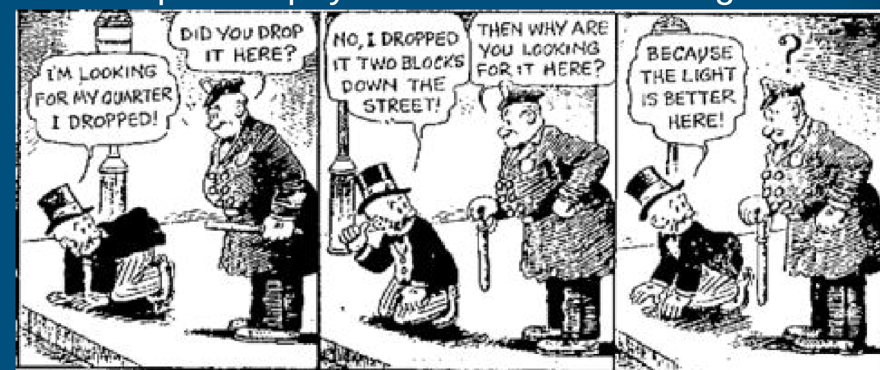
We expect(ed?) TeV scale new physics with sizable couplings but….

…no tangible evidence for new physics and no hint of the scale!

What about solutions to (some/all) SM shortcomings *below Fermi scale* $E < G_F^{-1/2}$?



"The particle physicist and the cosmologist…"



- Must have very weak couplings ➔ "*Light* Hidden Sector"

- Received much less attention recently:
  - PS 191: early 1980s
  - CHARM: 1980s
  - NuTeV: 1990s
  - DONUT: late 1990s - early 2000

New Physics prospects

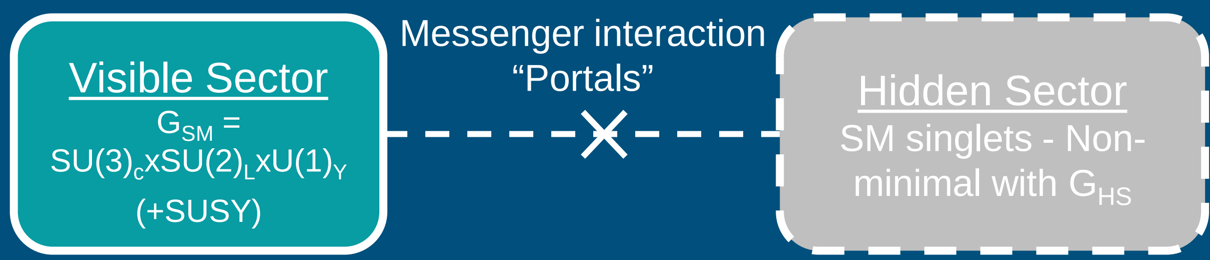
- Two possibilities for Beyond Standard Model with light particles
  1. Wider theory exist at new high energy scale (SUSY, extra dim., etc) with degrees of freedom that stay relevant at low energies. Particles may be light by dynamic effects
  2. SM + Hidden Sector with light messengers is all there is up to Planck scale – no new visible scale
  3. or both…

  ➔ Natural assumption: *We know we have a dark sector*

- Powerful constraints imposed by cosmological and astrophysical observations
  - Relic dark matter density
  - Big Bang Nucleosynthesis
  - CMB
  - Structure formation
  - Supernovae and white dwarf cooling
  - Baryon asymmetry
  - …

New Physics prospects in Hidden Sector

$$\mathcal{L}_{World} = \mathcal{L}_{SM} + \mathcal{L}_{mediation} + \mathcal{L}_{HS}$$



- New hidden particles are singlet under the SM gauge group
- Composite operators (hoping there is not just gravity…) $\mathcal{L}_{mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{HS}^{(k)} \mathcal{O}_{SM}^{(l)}}{\Lambda^n}$
  - ➔ Makes up "portals" between SM and Hidden Sector
  - No knowledge of hidden scale but hidden particles participating in portals may be light

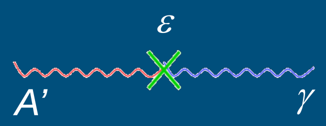
➔ *Dynamics of Hidden Sector may drive dynamics and anomalies of Visible Sector!*

- ➔ *Dark Matter candidates comes for "free" – stable or unstable*

New Physics prospects in Hidden Sector

- Standard Model portals:
  - **D = 2: Vector portal**

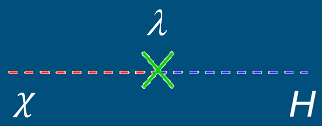
    ν_i



    - Kinetic mixing with massive dark/secluded/paraphoton A' : $\frac{1}{2}\varepsilon F^{SM}_{\mu\nu} F^{\mu\nu}_{HS}$

    ➔Motivated in part by idea of "mirror world" restoring L/R symmetry, dark matter (AMS e^+ excess), g-2 anomaly, …

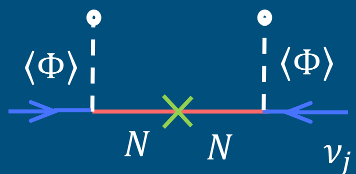
  - **D = 2: Scalar portal**



    - Mass mixing with dark singlet scalar χ : $(g\chi + \lambda\chi^2)H^\dagger H$

    ➔ Mass to Higgs boson and mass generation in dark sector, inflaton, dark phase transitions BAU, dark matter,…

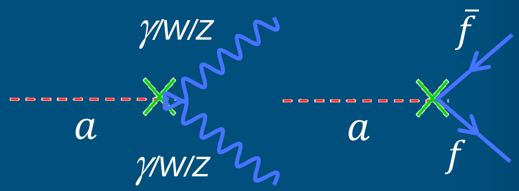
  - **D = 5/2: Neutrino portal**



    - Mixing with right-handed neutrino N (Heavy Neutral Lepton): $Y_{I\ell} H^\dagger \overline{N}_I L_\ell$

    ➔ Neutrino oscillation, baryon asymmetry, dark matter

  - **D = 4: Axion portal**



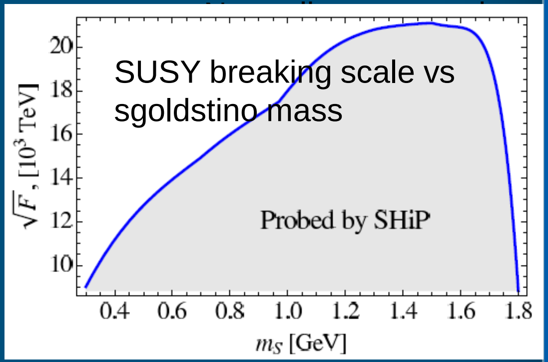
    - Mixing with Axion Like Particles, pseudo-scalars pNGB, axial vectors *a* : $\frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi$, etc

    ➔ Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale F

    ➔ Extended Higgs, SUSY breaking, dark matter, possibility of inflaton,…

New Physics prospects in Hidden Sector

- **And higher dimensional operator portals**
  - Chern-Simons portal (vector portal)
  - …
- **SUper-SYmmetric "portals"**
  - Some of SUSY low-energy parameter space open to complementary searches
  - Sgoldstino S(P) : $\frac{M_{\gamma\gamma}}{F} S F^{\mu\nu} F_{\mu\nu}$
    - Massless at tree level but massive via loop corrections
    - Naturally light in no-scale SUGRA and GMSB
    - Direct production: gg fusion
    - Indirect production: heavy hadron decays $D \to \pi S(\mathrm{P})$ $D_s \to K^+ S(P)$
    - Decay: $X \to \pi^+\pi^-, \pi^0\pi^0, l^+l^-, \gamma\gamma$
  - Neutralino in R-Parity Violating SUSY
    - LSP can decay into SM particles
    - Light neutralino with long lifetime $\tau_{\tilde{\chi}} < 0.1s$ (BBN)
    - Production: heavy meson decays $D \to \nu\tilde{\chi}$, $D^\pm \to l^\pm\tilde{\chi}$
    - Decay: $\tilde{\chi} \to l^+l^-\nu$
  - Hidden Photinos, axinos and saxions….



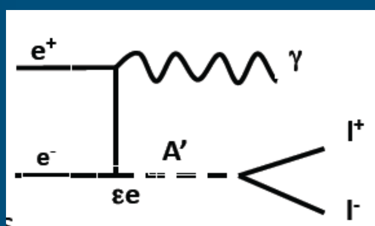
➔ A very large variety of models based on these or mixtures thereof

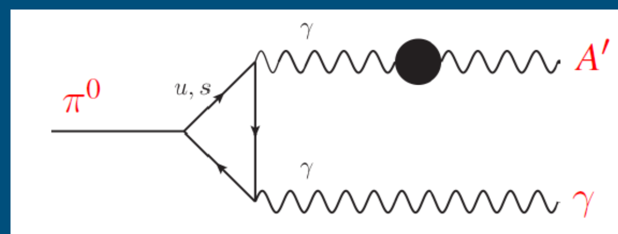
- Assumption here: invisible decay $\chi\bar{\chi}$ is absent or sub-dominant, $m_\chi > \frac{1}{2} m_{portal}$, where χ hidden particle

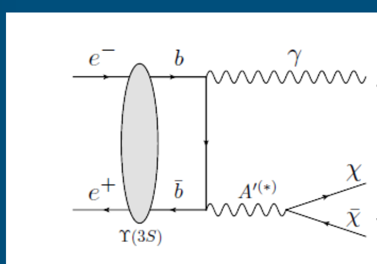
Status of dark photon searches

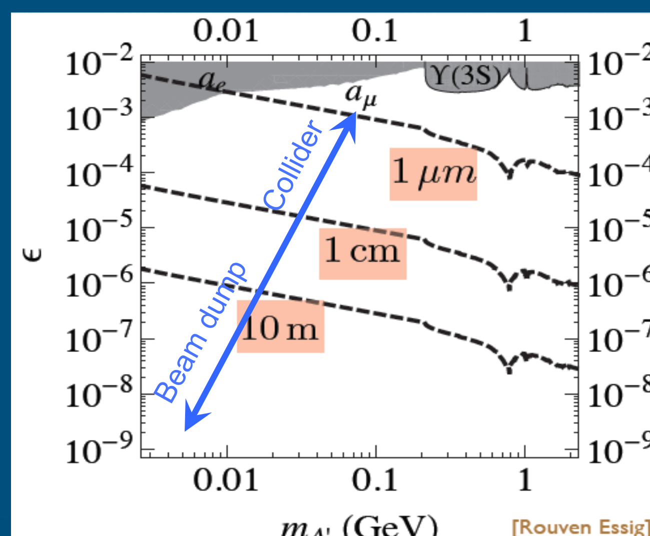
- Mass $m_{A'}$< few GeVs, otherwise $\bar{p}$ excess in many models

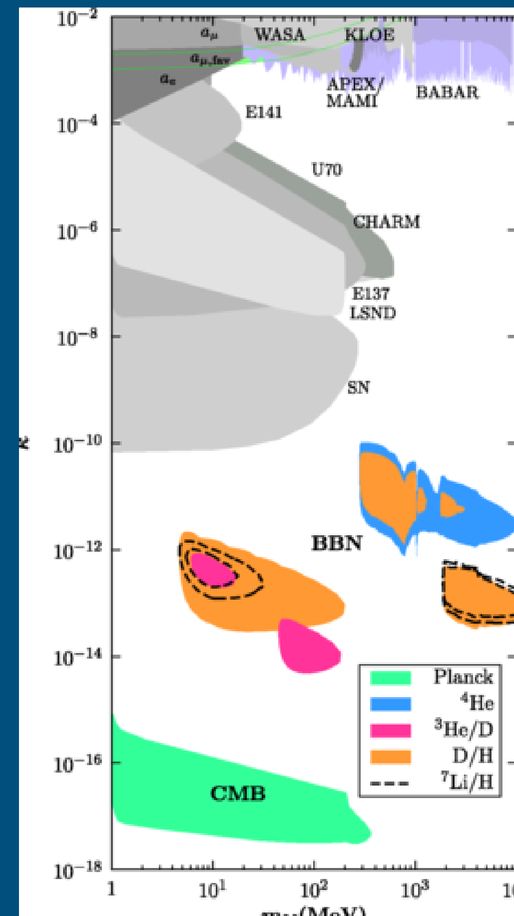
- Production
  - Bremsstrahlung (e, p), direct QCD production $q\bar{\bar{q}} \rightarrow A', qg \rightarrow A'q$, meson decays $(\pi^0, \eta,\ \omega,\ \eta', \ldots)$
  - ➔ Electron fixed-target experiments
  - ➔ B, D factories
  - ➔ Proton beam-dumps!











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Status of dark photon searches

- B factories (D factories BESIII) (light resonance search)
  - $e^+e^- \rightarrow \Upsilon \rightarrow \gamma A'$, radiative decays $e^+e^- \rightarrow \Upsilon(2) \rightarrow \Upsilon(1s)\pi^+\pi^-$ where $\Upsilon(1s) \rightarrow \gamma A'$

  ➔ BaBar (514 fb^{-1}) : Generic search for neutral resonance with displaced vertex 1 – 50 cm ,

  $$A' \rightarrow e^+e^-, \mu^+\mu^-, (e^\pm\mu^\mp), \pi^+\pi^-K^+K^-, (\pi^\pm K^\mp), \text{ 0.2 – 10 GeV}$$

  ➔ Belle: Radiative decays $\Upsilon(2S) \rightarrow \Upsilon(1s)\pi^+\pi^- \rightarrow \gamma + invisible$ (24.7 fb^{-1} of *Υ(2S)* data);

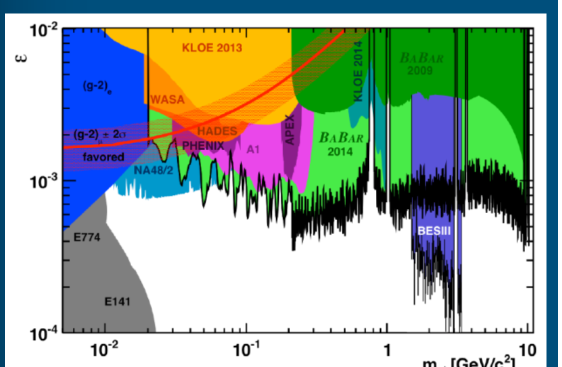
  $e^+e^- \rightarrow A'\mu^+\mu^-,\ A' \rightarrow l^+l^-,\ \pi^+\pi^-,\ K^+K^-$, Prompt and displaced vertices up to 10cm

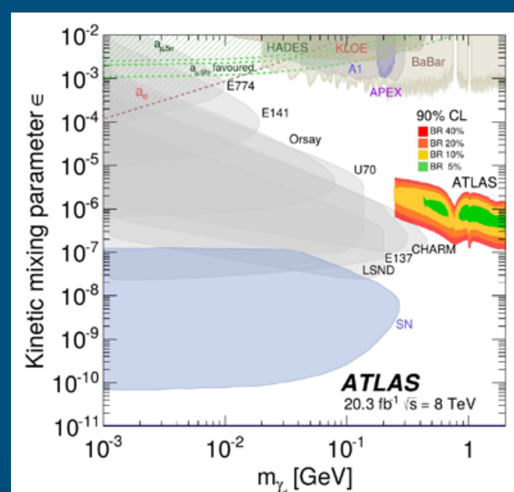
- Electron dumps: HPS $A' \rightarrow e^+e^-, \mu^+\mu^-$, 0.02 – 1 GeV/c^2 (*PADME, NA64*)

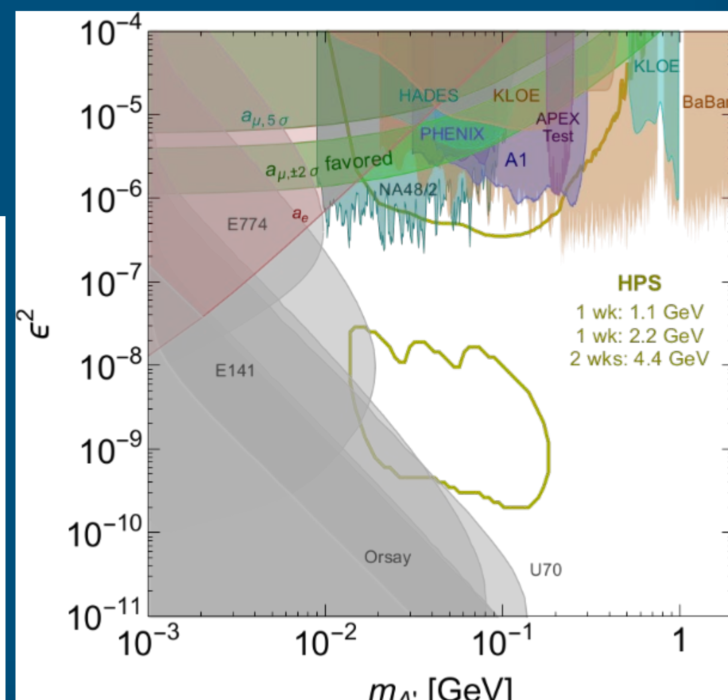
- NA48/62: $\pi^0 \rightarrow \gamma A'$, 9-70 MeV/c^2

  Prospects $K^+ \rightarrow \pi^+ A',\ A' \rightarrow l^+l^-$ lower background and higher acceptance, 10 – 350 MeV/c^2

- LHC: Not ideal….
  - Large background and not many photons
  - Displaced vertices: “displaced lepton-jets”



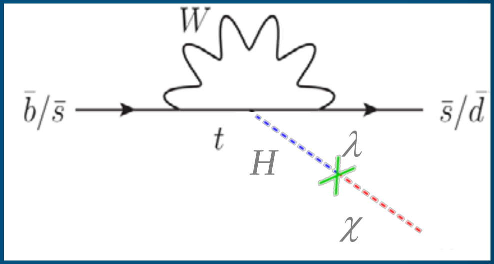


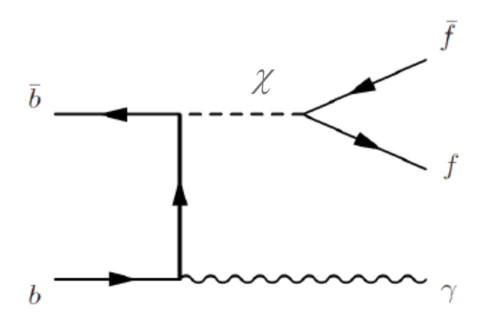


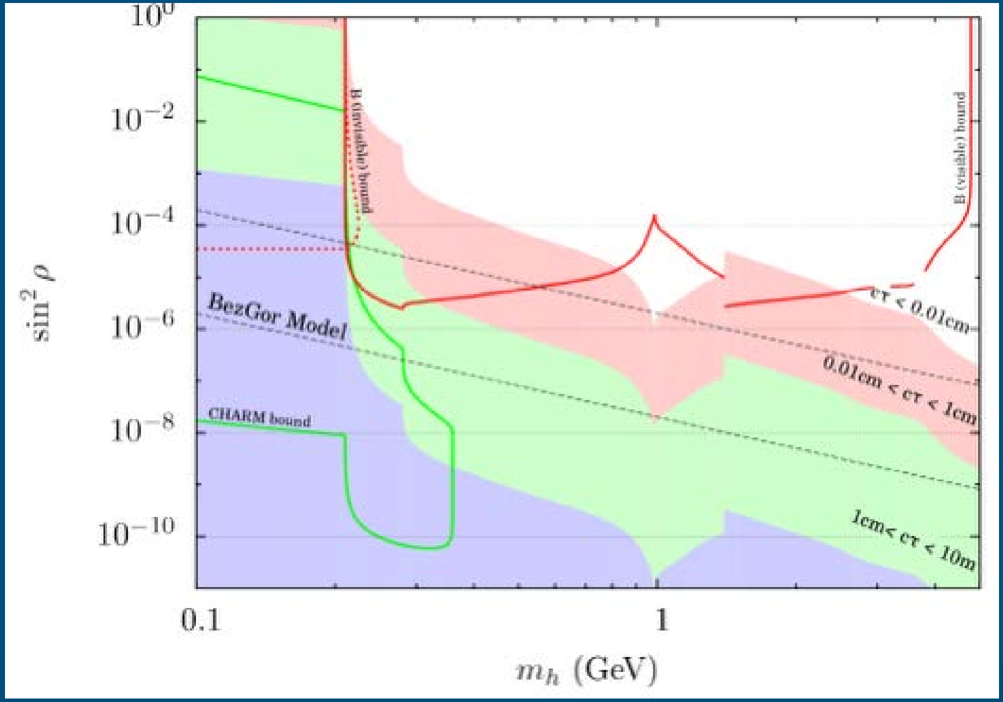
Status of dark scalar searches

- Similar signatures to dark photon
  - Interpretation of [limits on] signal in framework of model

- Production:
  - Rare meson decays e.g. $B \rightarrow K^{(*)}\chi,\ \ K \rightarrow \pi\chi,\ \Upsilon \rightarrow \gamma + visible/invisible$
    - Production in D decays suppressed, i.e. $(m_t^2|V_{ts}^* V_{tb}|)^2/(m_b^2|V_{cb}^* V_{ub}|)^2$
  - (Dark Higgsstrahlung)
  - Direct $p + target \rightarrow X\chi$

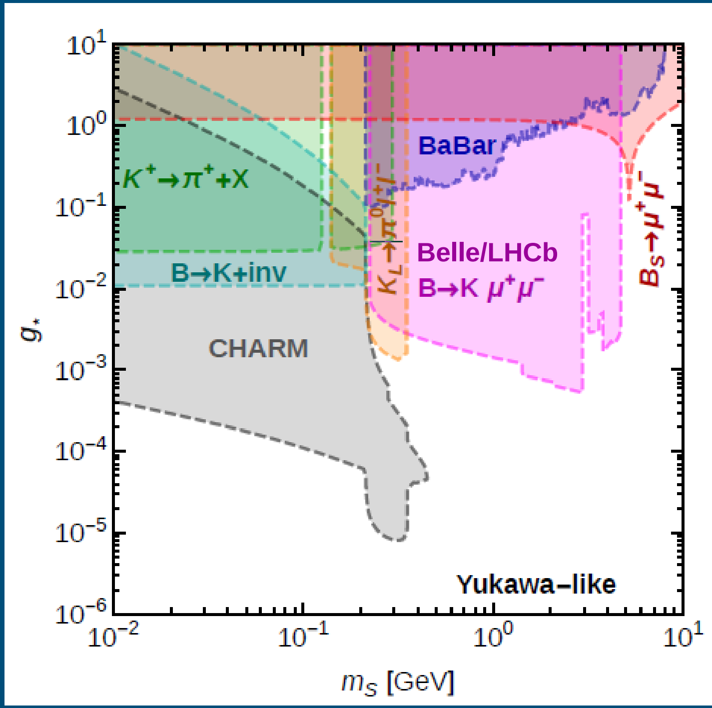


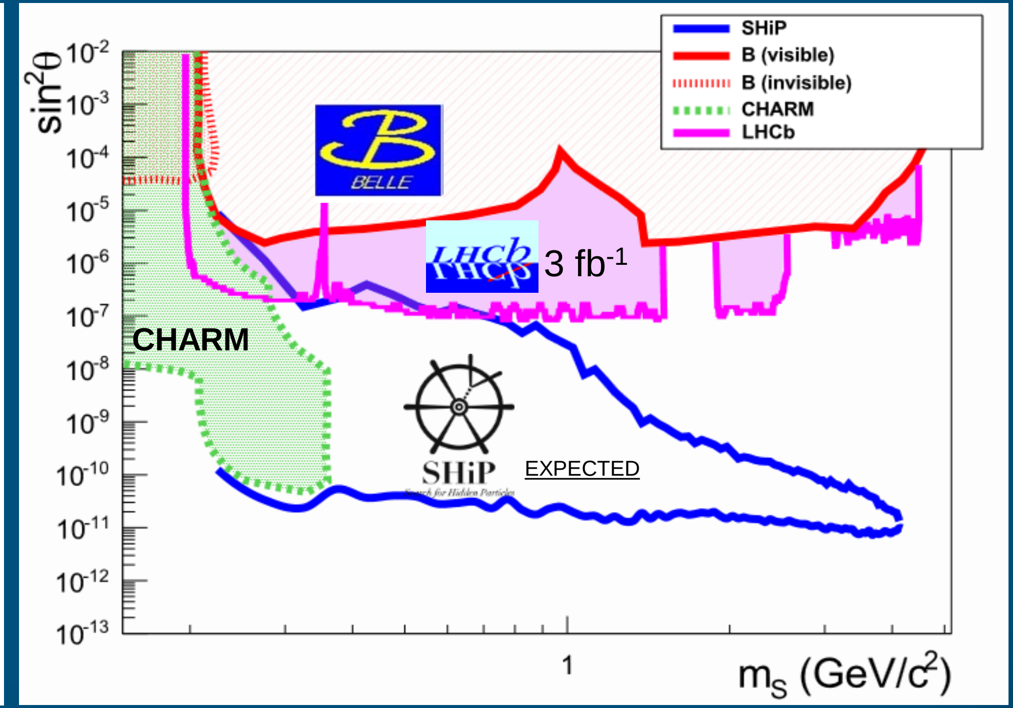




Status of dark scalar searches

- BaBar: $\Upsilon \rightarrow \gamma\chi,\ \chi \rightarrow \mu\mu, \tau\tau, hh$
- Belle: $B \rightarrow K\chi,\ \chi \rightarrow \mu^+\mu^-,$
  $\Upsilon \rightarrow \gamma + invisible$
- LHCb (3fb^{-1}):
  - $B \rightarrow K\chi,\ \chi \rightarrow \mu^+\mu^-,$ both prompt and displaced vertices
  - Analysis largely background free → sensitivity scales with yield of B

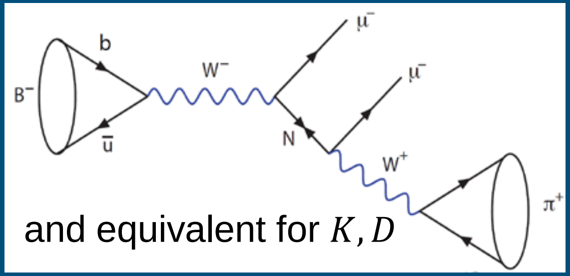




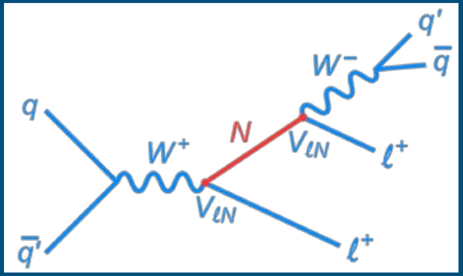
Status of 'heavy' neutrino searches

	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

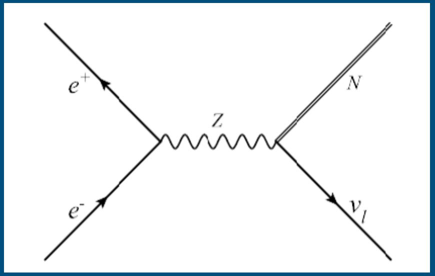
- Production:
  - Leptonic, semi-leptonic decays of hadrons
  - W, Z decays
  - $\Gamma_N \sim |V_{\alpha N}|^2 G_F^2 M_N^5$



B factories/LHCb

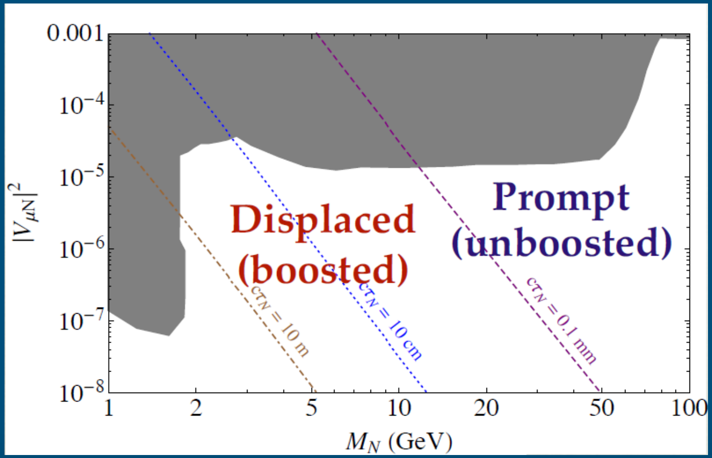


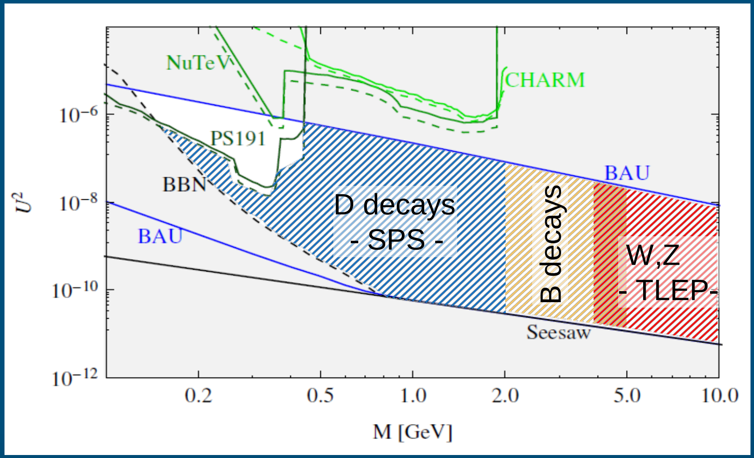
Hadron colliders



Z factories

Below BAU (e.g. N_2, N_3 in νMSM)



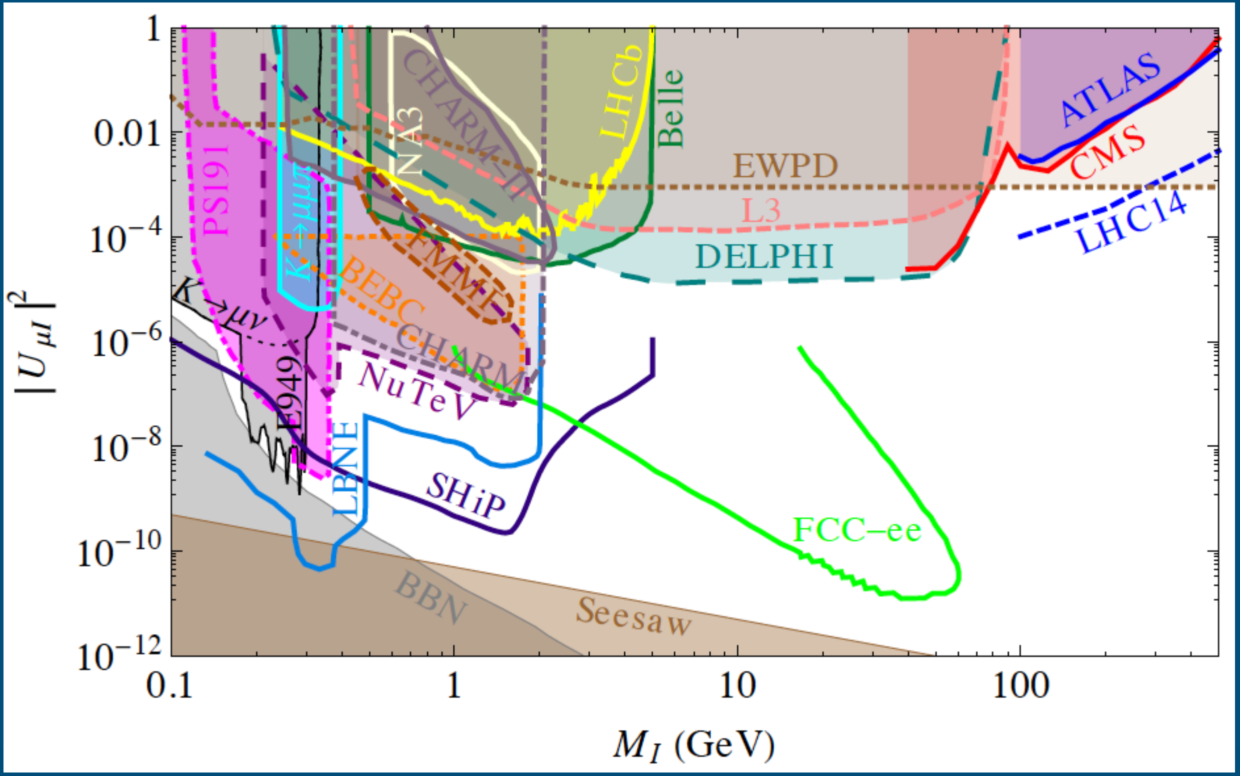


Status of 'heavy' neutrino searches

- BABAR (4.7x10[8] $B\bar{B}$, 561 fb^{-1}): $B^+ \to X^- l^+ l'^+$; $X^- = K^-, \pi^-, \rho^-, K^{*-}, D^-$; $l^+ l'^+ = e^+, \mu^+$
- Belle (7.7x10[8] $B\bar{B}$, 711 fb^{-1}): $B \to XlN$, $X = D^{(*)}$, light meson or nothing; $N = l\pi$, $l = e, \mu$
- LHCb (3 fb^{-1}): $B^- \to X^+ \mu^- \mu^-$; $X^+ = \pi^+, D^+, D^{*+}, D_s^+, D^0\pi^+, K^+$

  $D^+_{(s)} \to \pi^- \mu^+ \mu^+$
- LHC (ATLAS/CMS ~20 fb^{-1}): $W \to Nl^{\pm}$; $N \to l^{\mp} W^{\pm}$; $W \to l\nu, q\bar{q}$, ~10^9 ν's for each 25 fb^{-1} from W's
- NA48/NA62: $K^+ \to l^+ N$, $N \to l\pi, l\rho$; 0.1 – 0.4 GeV

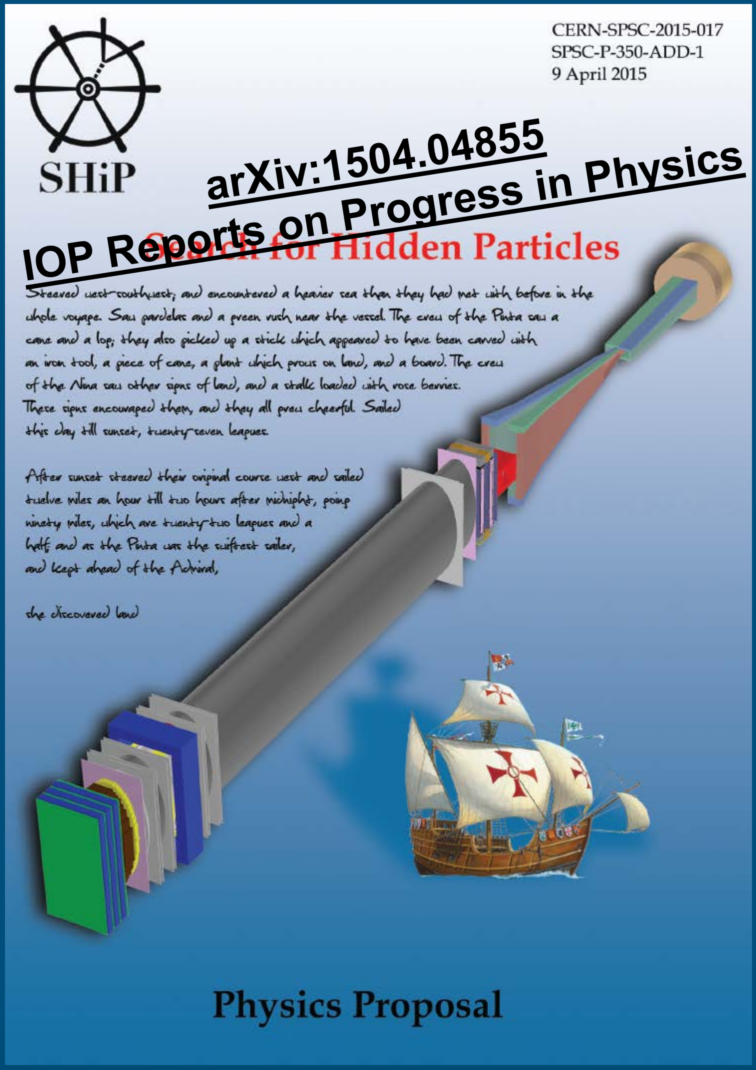
  $D^+_{(s)} \to l^+ N$, $N \to l\pi, l\rho$; 0.4 – 1.5 GeV, to be evaluated



SHiP Physics case

➔ *Large and highly interesting territory still remains!*

➔ *SHiP has significant sensitivity to all of these up to O(10) GeV!*



- ➔ SHIP Physics Proposal
  - >80 theorist authors
  - >200 pages
  - >1000 references!

- Setting limits is “easy” but theorist home work:
  - In case of discover, how do we call the new particle(s)!?

light HS phenomenology at beam dump

- Cosmologically interesting and experimentally accessible $m_{HS} \sim \mathcal{O}(MeV - GeV)$
  - ➔ Production in π, K, D, B decays, photons → High A and Z target
  - ➔ Most common 2-body decays → Full reconstruction and identification

Models	Final states
Neutrino portal, SUSY neutralino	$\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp, \quad \rho^\pm \to \pi^\pm\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	$\ell^+\ell^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-, K^+K^-$
Neutrino portal ,SUSY neutralino, axino	$\ell^+\ell^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$
SUSY sgoldstino	$\pi^0\pi^0$

- Production and decay rates are very suppressed relative to SM
  - Production branching ratios $\mathcal{O}(10^{-10})$ → Largest possible number of protons
  - Large neutrino background → Short λ target
  - Travel unperturbed through *ordinary* matter → Allow filtering out background
  - Long-lived objects → Large decay volume

➔ Challenge is background suppression ➔ requires extremely careful estimation

➔ Fixed-target ("beam-dump") experiment with large decay volume

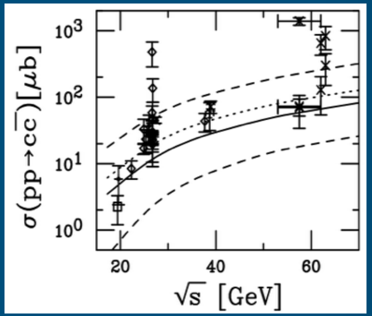
➔ Side benefit: Optimizing for heavy meson decays also optimizes facility for ν_τ physics

- $Br(D_s \to \tau \quad + \nu_\tau) \sim$ 5.6% : 10^{15}

Experimental features at SHiP facility

Proposal: ‘*Beam dump’-like experiment at the SPS*

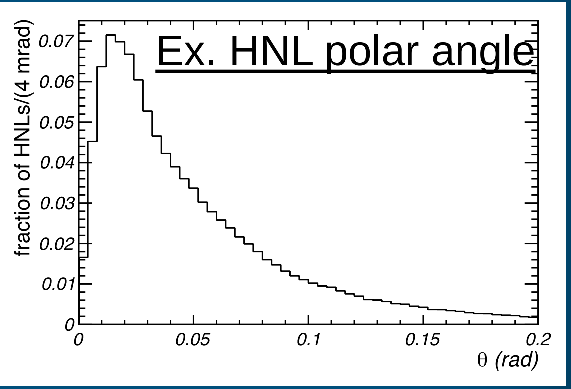
➔ SPS: 4×10^{13} / 7s @ 400 GeV = 500 kW → 2×10^{20} in 5 years (similar to CNGS)



1. Parallel operation with CERN North Area LHC, AWAKE, etc
2. Slow beam extraction of 1s
   - ➔ Beam dilution on target
   - ➔ Reduce combinatorial background
3. As uniform extraction as possible for target and combinatorial background/occupancy

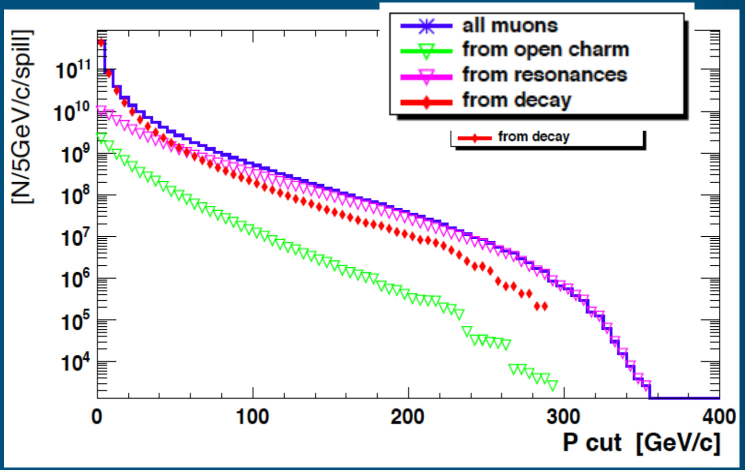
1. Muon shield to range out flux of muons
2. Away from walls and minimize surrounding structures to reduce neutrino/muon interactions in proximity of detector

7. Evacuated detector volume to reduce neutrino interactions
8. Detector as close as possible to target to maximize acceptance
   - Hidden particles in D and B decays have significant p_T



Schematic Principle of Experimental Setup

- Initial reduction of beam induced background:
  - Heavy target
  - Hadron absorber
  - Muon shield
    - → Without: Rate at detector $5x10^9$ muons / $5x10^{13}$ p.o.t.
    - → Biased towards higher momenta muons due to heavy target



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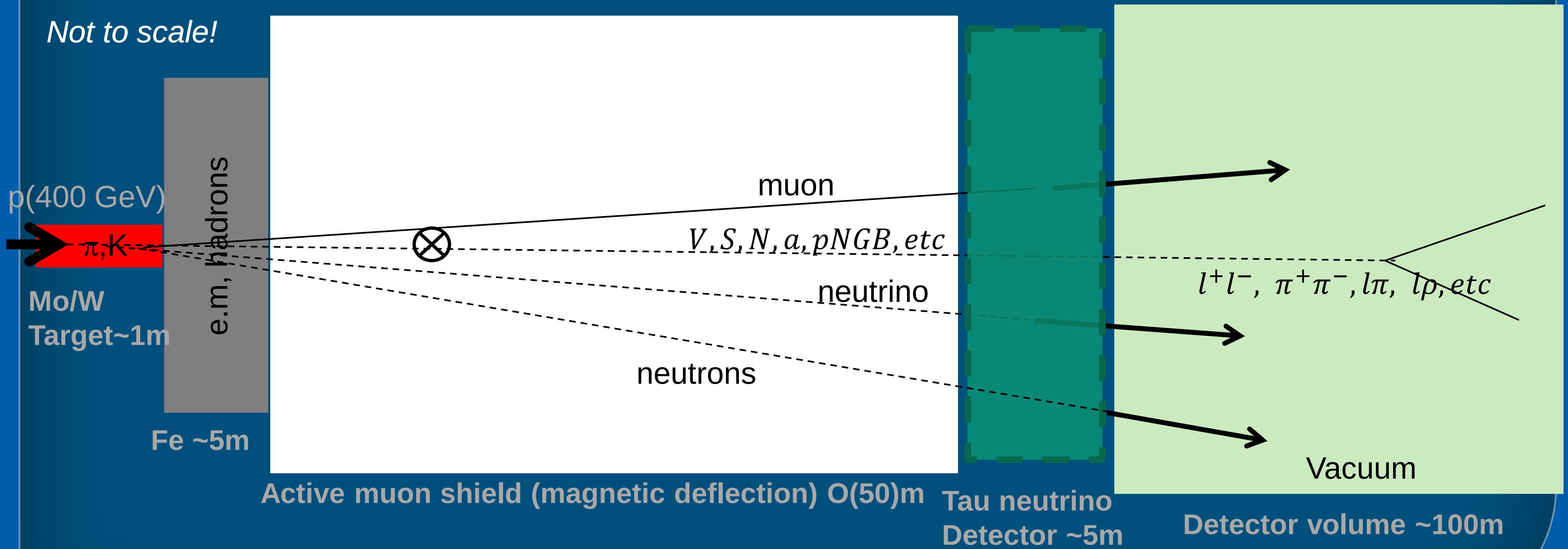


Residual background sources

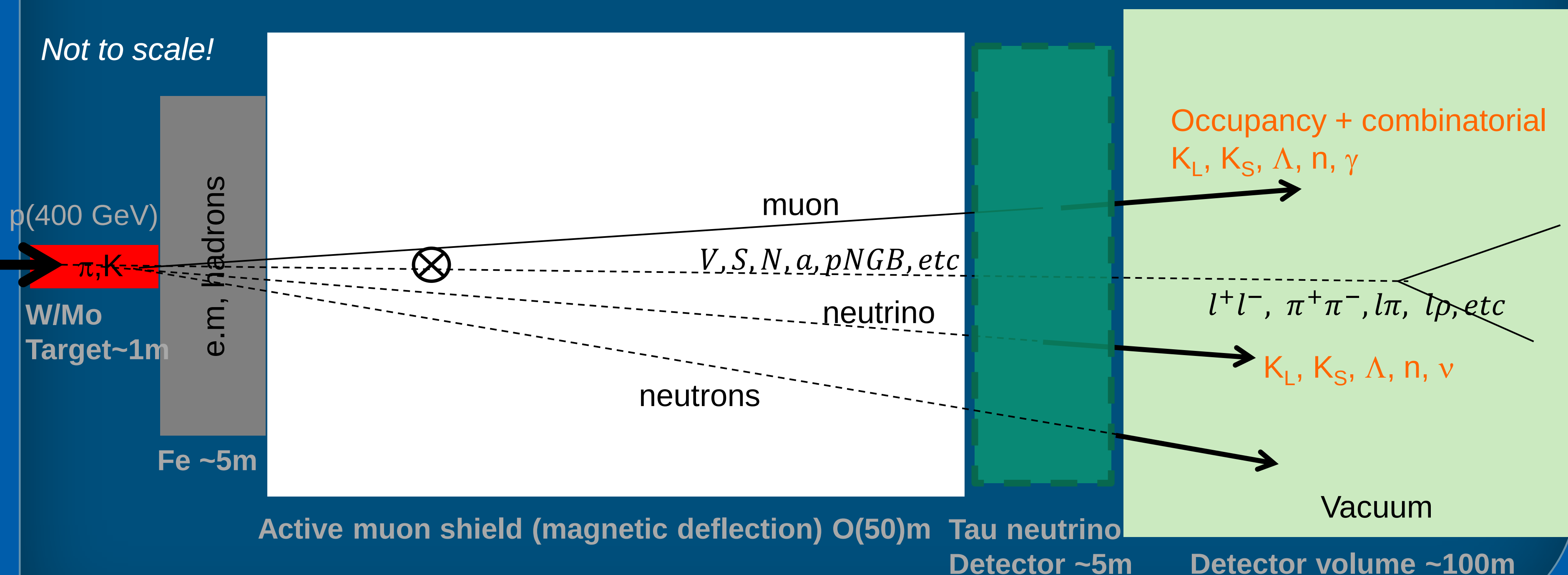
- Residual backgrounds sources:
  1. Neutrino inelastic scattering (e.g. $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu\pi\nu$)
  2. Muon inelastic scattering
  3. Muon combinatorial (e.g. μμ with μ mis-ID)
  4. Neutrons
  5. Cosmics

Fraction of particles entering the vacuum vessel

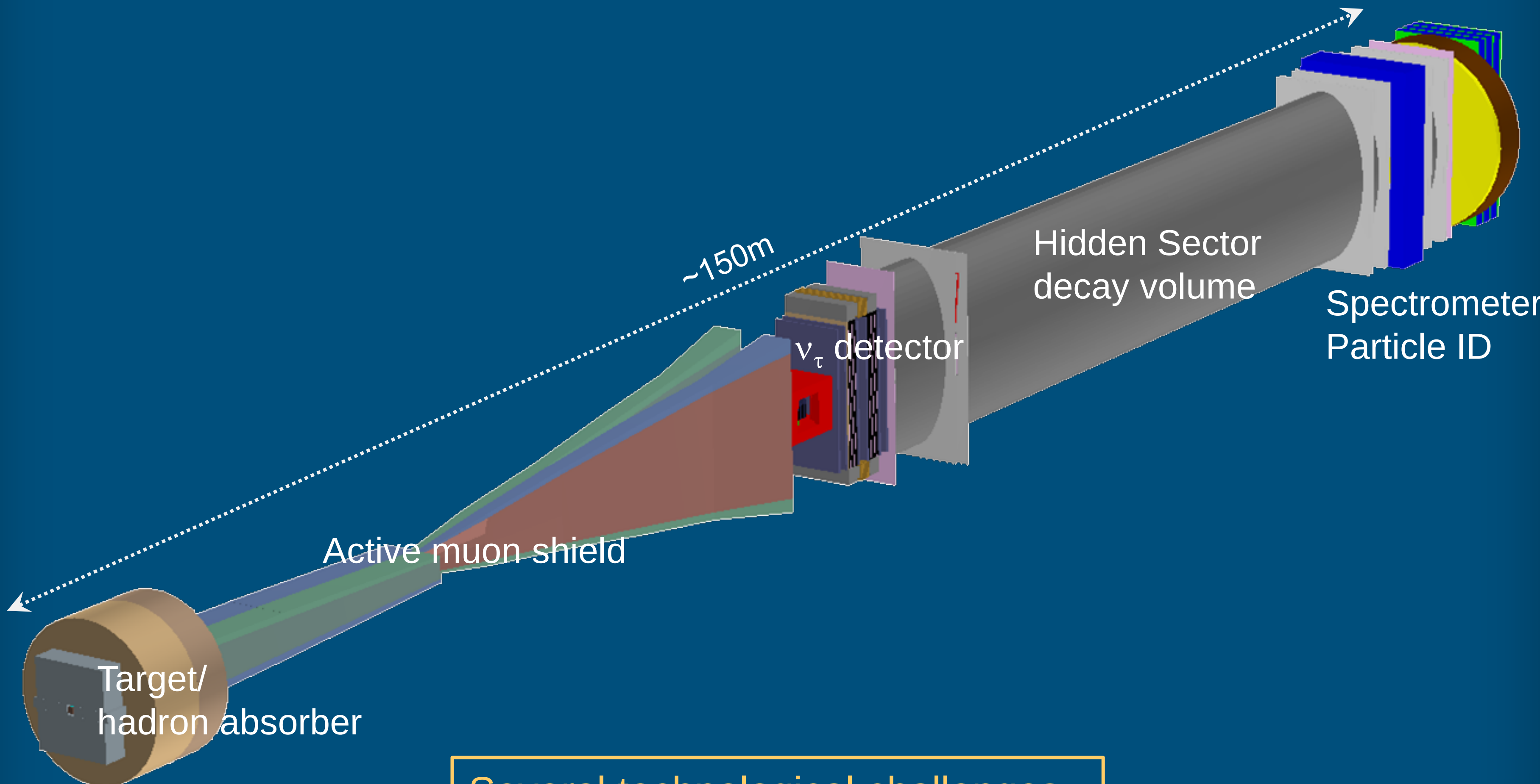
Per ν_μ CC interaction:

Particle	$Fraction_{Entering}$
Neutron	1.98
Λ	3.6×10^{-6}
K_S^0	3.6×10^{-6}
K_L^0	0.5%

Not to scale!



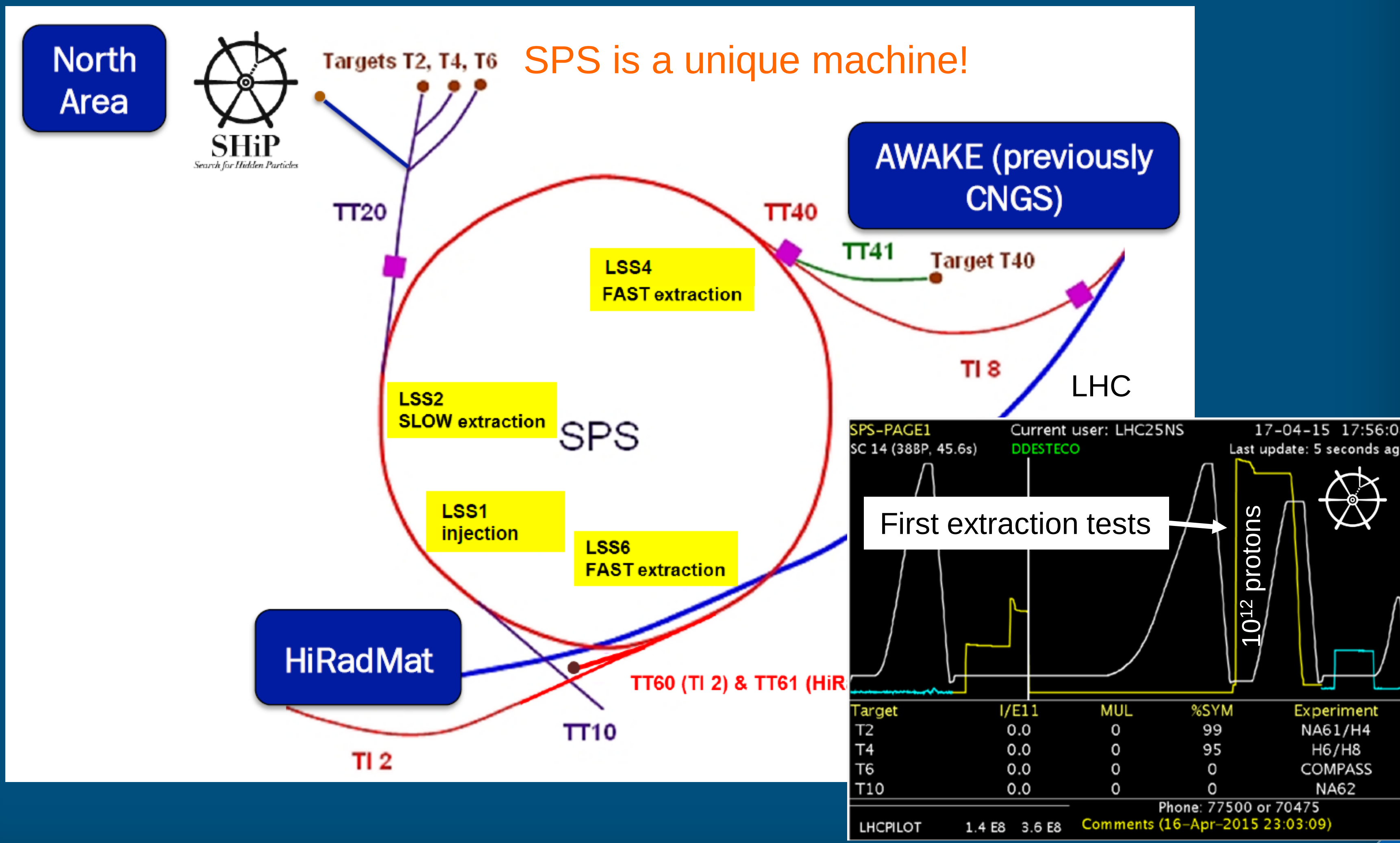
Overview of SHiP (TP)



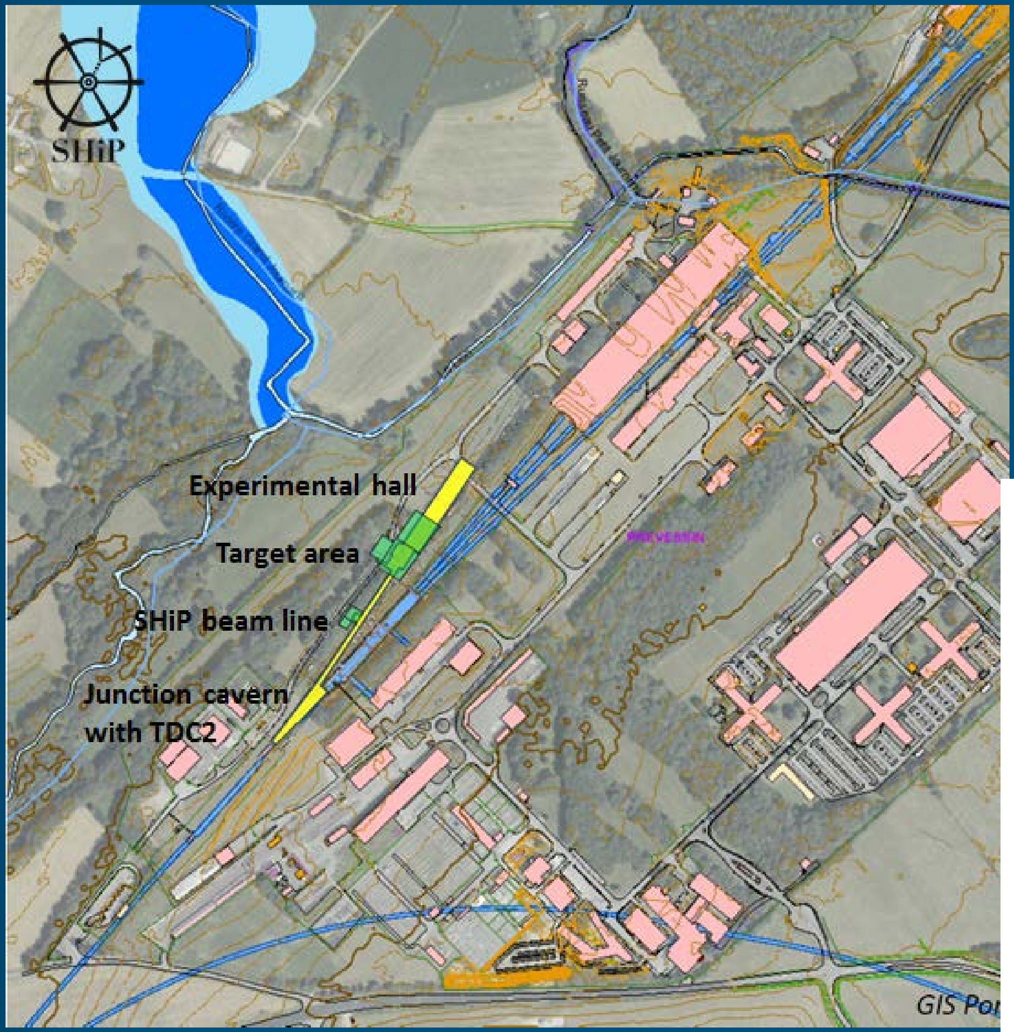
Several technological challenges

SHiP Location

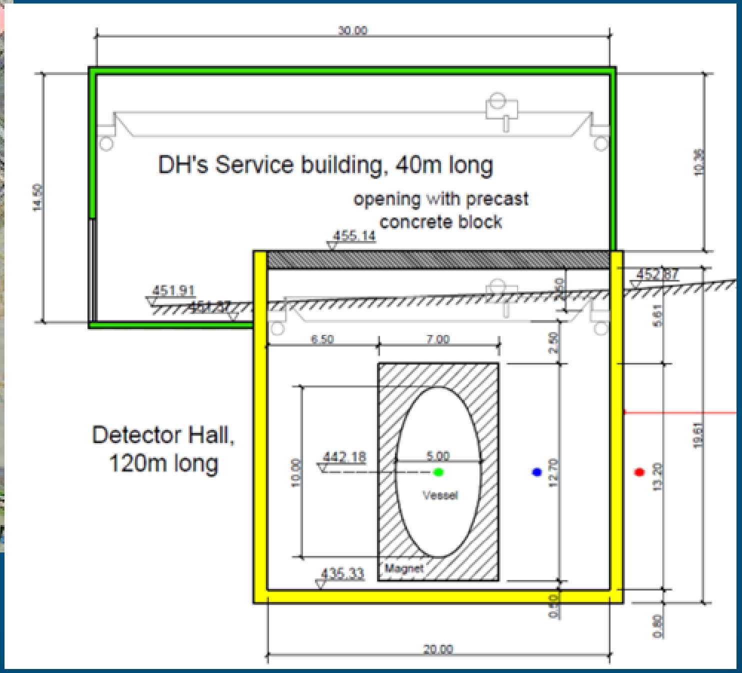
- Proposed location by CERN beams and support departments
  - 4×10^{13} protons on target at 400 GeV / 7s with slow extraction
  - 10^{6} spills / year ➔ 4×10^{19} p.o.t.



SHiP Facility at Prevessin North Area



- Civil engineering close to existing infrastructures
  - 8m safety margin required during operation of NA
  - 20 months required for work package to make junction cavern and rebuild beamline
  - 4-5 years in total



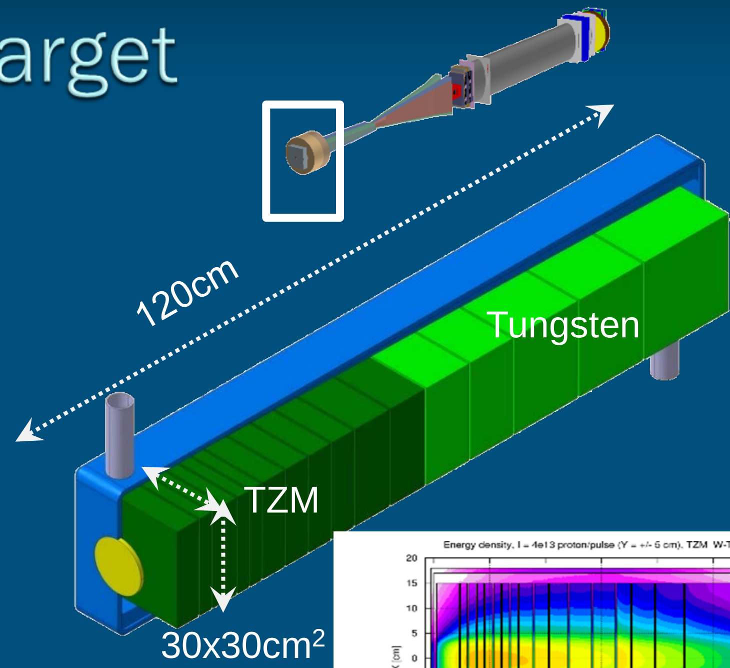
SHiP target

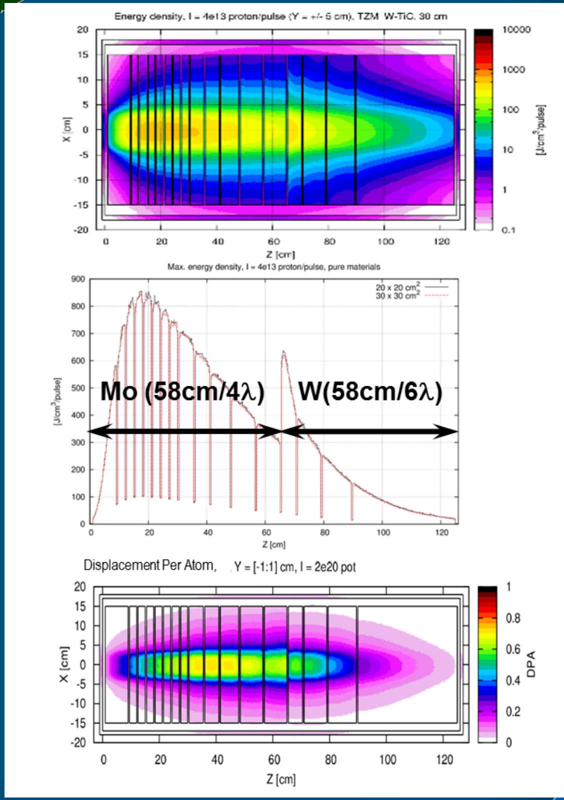
Design considerations with 4×10^{13} p / 7s

→ 355 kW average, 2.56 MW during 1s spill

- High temperature
- Compressive stresses
- Atomic displacement
- Erosion/corrosion
- Material properties as a function of irradiation
- Remote handling (Initial dose rate of 50 Sv/h…)

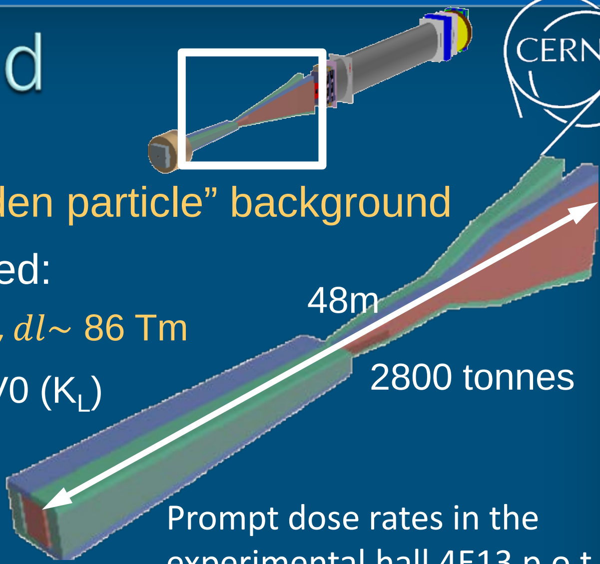
→ Hybrid solution: Mo allow TZM (4λ) + W(6λ)





	DONUT [1)]	CHARM [2)]	SHiP
Target material	W-alloy	Cu (variable ρ)	TZM + pure W
Momentum (GeV/c)	800	400	400
Intensity	0.8×10^{13}	1.3×10^{13}	**4×10^{13}**
Pulse length (s)	20	23×10^{-6}	1
Rep. rate (s)	60	~10	7.2
Beam energy (kJ)	1020	830	2560
Avg. beam power (spill) (kW)	51	3.4×10^{7} (fast)	2560
Avg. beam power (SC) (kW)	17	69	355
POT	Few 10^{17}	Few 10^{18}	**2×10^{20}**

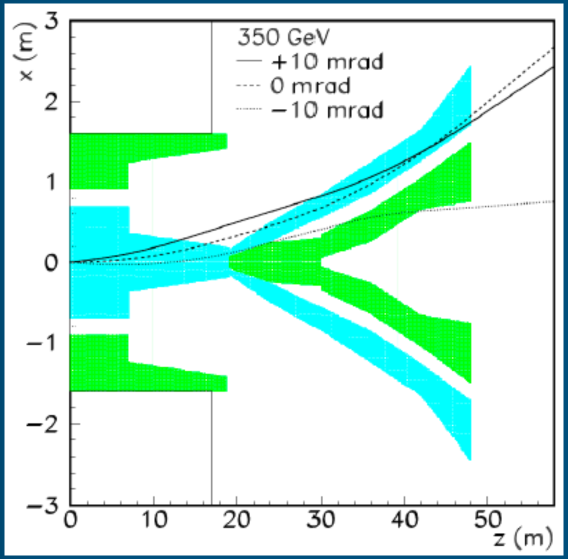
Active muon shield

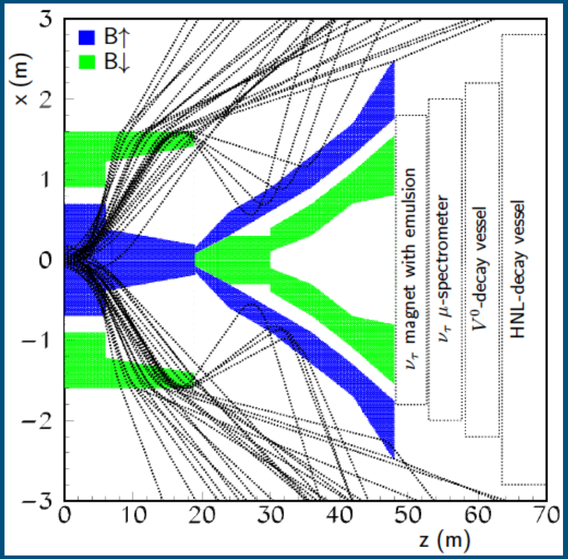


- Muon flux limit driven by emulsion based ν-detector and "hidden particle" background
- Passive and magnet sweeper/passive absorber options studied:
  - Conclusion: Shield based entirely on magnetic sweeping with $\int B_y\, dl \sim$ 86 Tm

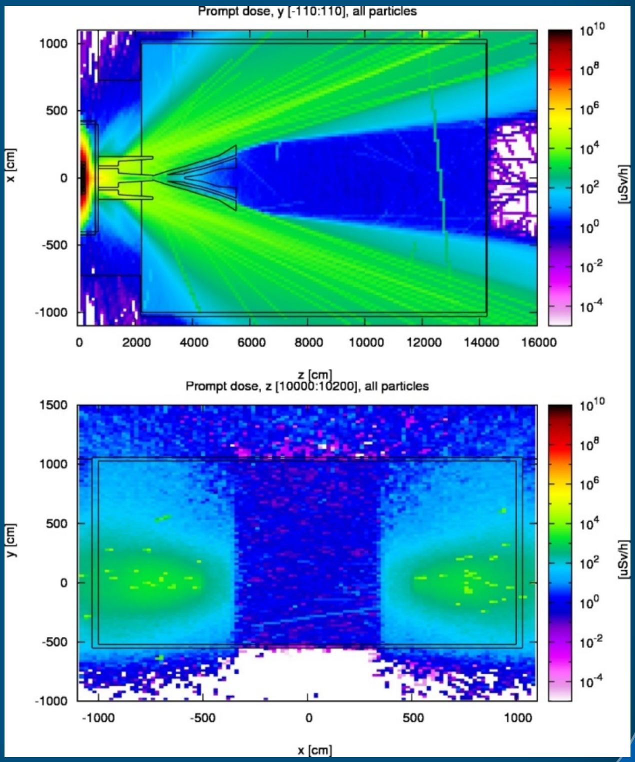
➔ <7×10^3 muons / spill (E_μ > 3 GeV) which can potentially produce V0 (K_L)

➔ Negligible occupancy



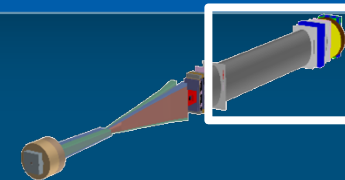


Prompt dose rates in the experimental hall 4E13 p.o.t. / 7s



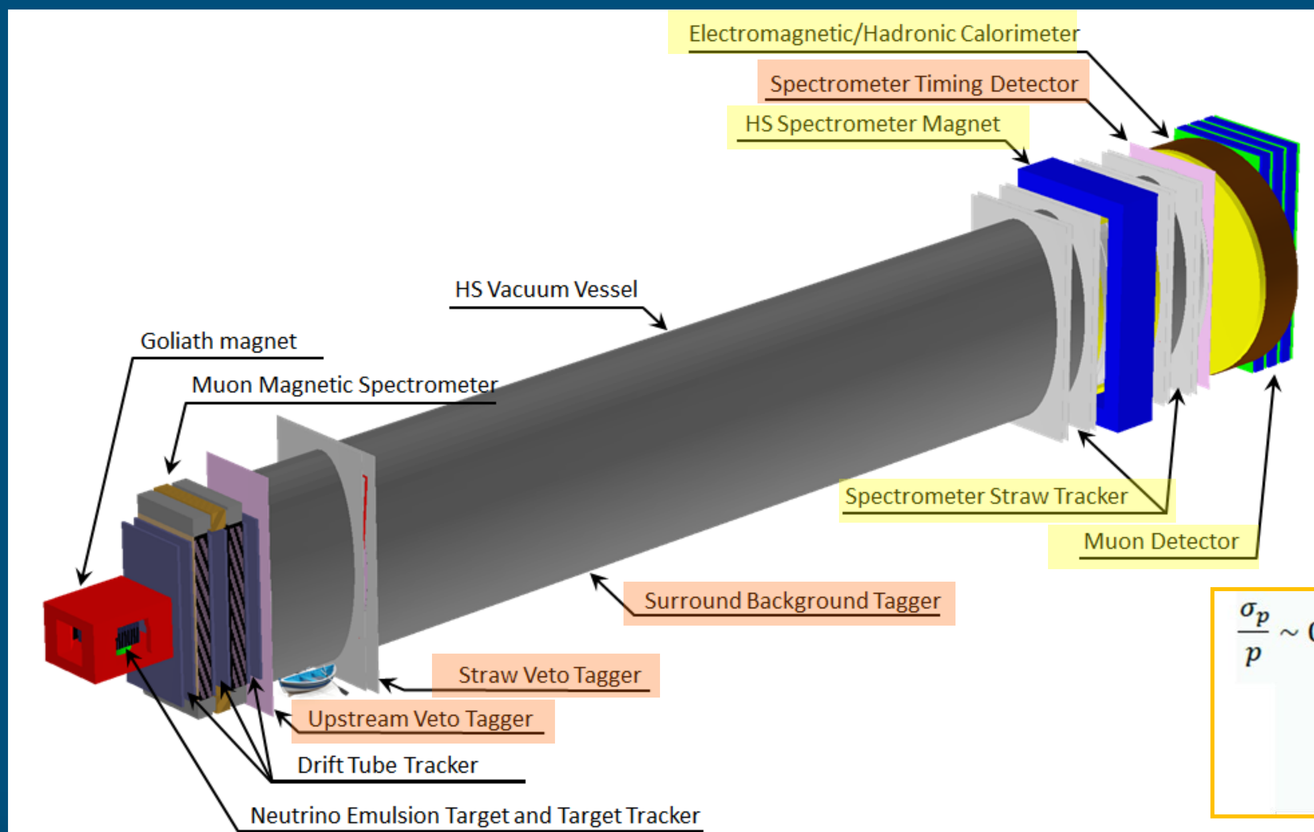
➔ Challenges: flux leakage, constant field profile, modelling magnet shape

HS detector as in TP



Detector concept

1. Large decay volume
2. Full reconstruction and particle identification of final states with e, $\mu, \pi^{\pm}, \gamma$ ($\pi^0, \rho^{\pm}$), (ν), and decays in flight
   - Magnetic spectrometer, electromagnetic calorimeter, hadron calorimeter/muon detector
   - Extended particle ID under investigation
3. Background identification
   - Timing detectors, surrounding and front veto taggers



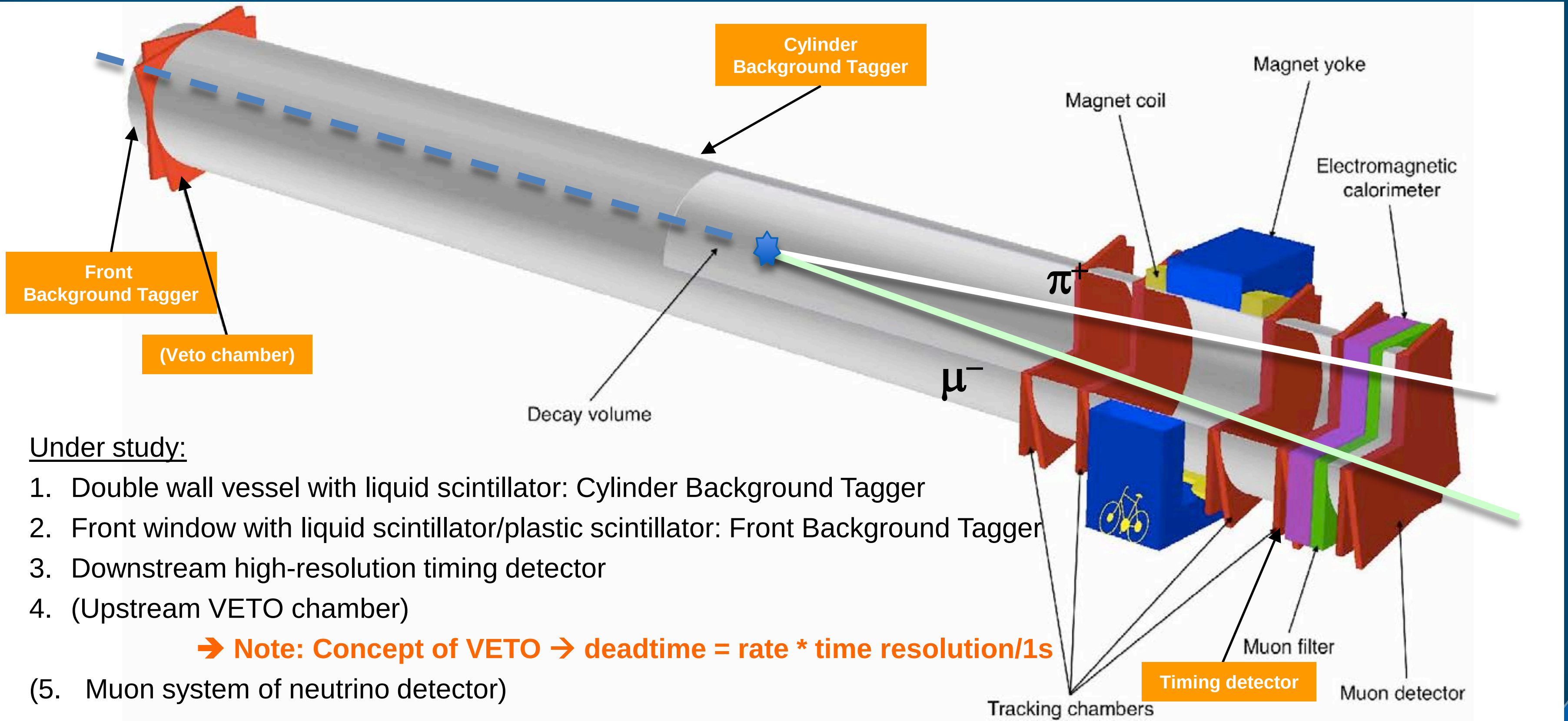
$$\frac{\sigma_p}{p} \sim 0.5\% \oplus 0.02\% \times p$$

$$\frac{\sigma_E}{E} \sim \frac{6\%}{\sqrt{E}}$$

$$\sigma_t \sim 100 \text{ ps}$$

Options for background suppression

- Residual backgrounds sources:
  1. Neutrino inelastic scattering (e.g. $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu\pi\nu$) ➔ Detector under vacuum, accompanying charged particles (tagging, timing), topological
  2. Muon inelastic scattering ➔ Accompanying charged particles (tagging, timing), topological
  3. Muon combinatorial (e.g. $\mu\mu$ with μ mis-ID) ➔ Tagging, timing and topological
  4. Neutrons ➔ Tagging, topological
  5. Cosmics ➔ Tagging, timing and topological

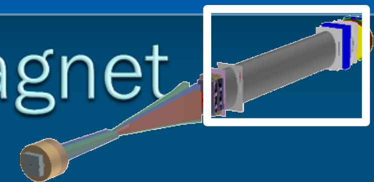


Under study:
1. Double wall vessel with liquid scintillator: Cylinder Background Tagger
2. Front window with liquid scintillator/plastic scintillator: Front Background Tagger
3. Downstream high-resolution timing detector
4. (Upstream VETO chamber)

➔ Note: Concept of VETO → deadtime = rate * time resolution/1s

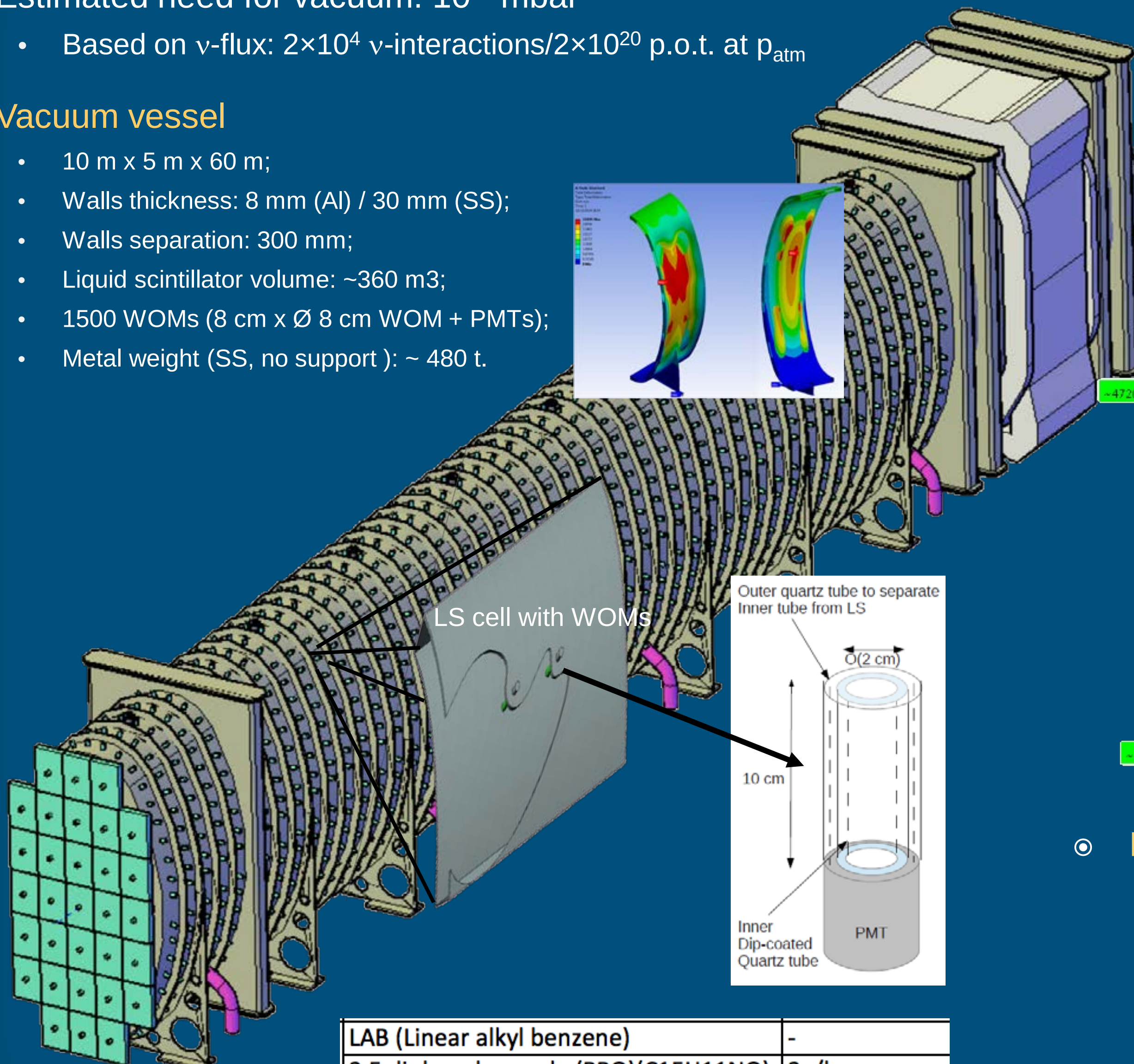
(5. Muon system of neutrino detector)

TP: Vessel and spectrometer magnet

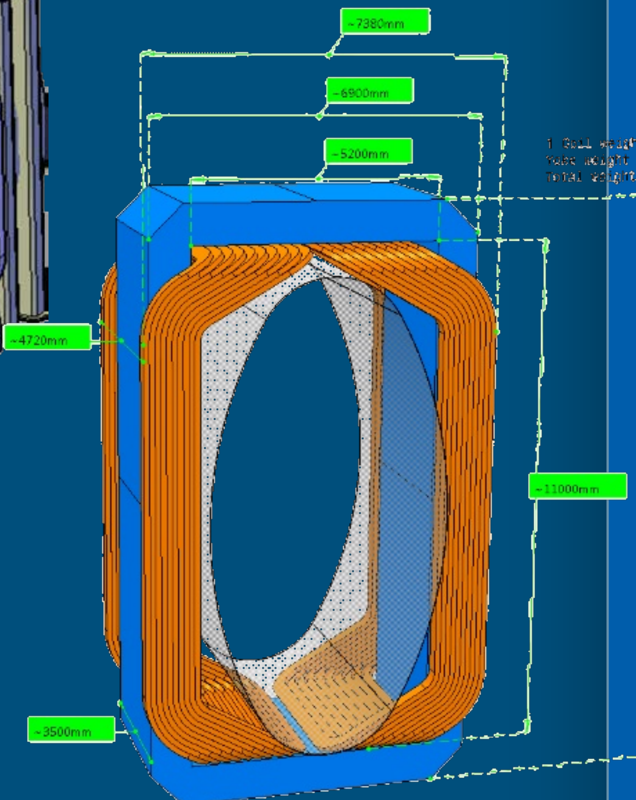


- Estimated need for vacuum: 10^{-3} mbar
  - Based on ν-flux: 2×10^4 ν-interactions/2×10^{20} p.o.t. at p_{atm}

- Vacuum vessel
  - 10 m x 5 m x 60 m;
  - Walls thickness: 8 mm (Al) / 30 mm (SS);
  - Walls separation: 300 mm;
  - Liquid scintillator volume: ~360 m3;
  - 1500 WOMs (8 cm x Ø 8 cm WOM + PMTs);
  - Metal weight (SS, no support): ~ 480 t.

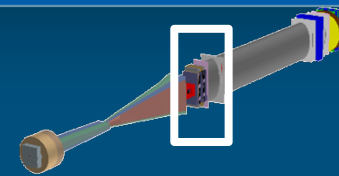


LAB (Linear alkyl benzene)	-
2.5 diphenyl oxazole (PPO)(C15H11NO)	3g/l

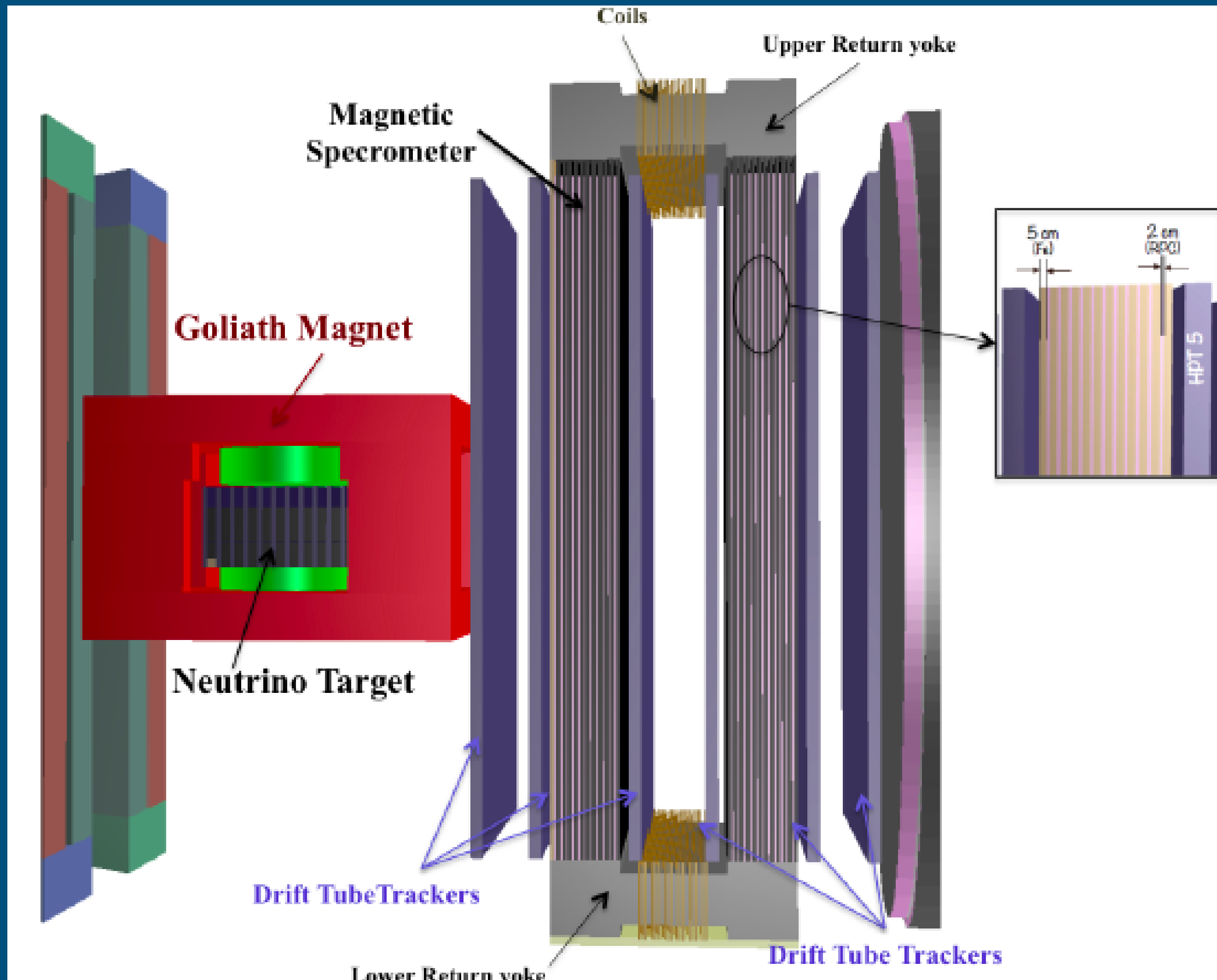


- Low power magnet designed
  - Field integral: 0.65Tm over 5m
  - Current 2500 A (1.7 A/mm2
  - Power consumption < 1 MW
  - Weight ~800 tonnes

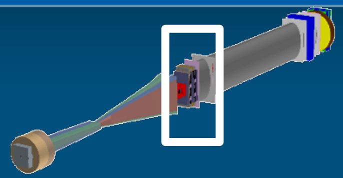
Tau neutrino detector



Follows the OPERA concept



Neutrino detection



- **Unique capability of detecting all three neutrino flavours**
  - Neutrino interaction +
  - \+ ν_e : electrons producing e.m. shower in emulsion target
  - \+ ν_μ : muons identified by target tracker and the muon spectrometer of the ν_τ detector
  - \+ ν_τ / $\bar{\nu}_\tau$: τ decay vertices in emulsion target

	ε_{tot} (%)
$\tau \rightarrow \mu X$	60
$\tau \rightarrow hX$	62
$\tau \rightarrow 3hX$	63
$\tau \rightarrow eX$	56

- **Separation between ν_τ and $\bar{\nu}_\tau$ by charge measurement**
  - charge of hadrons is measured by CES
  - charge of muons is measured by CES and magnetic spectrometer

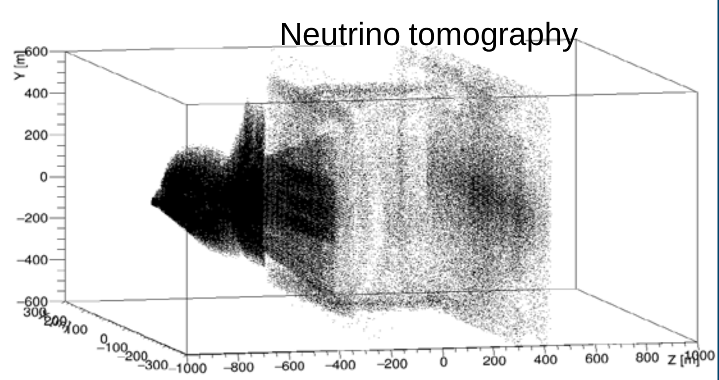
	$\tau \rightarrow hX$	$\tau \rightarrow 3hX$	$\tau \rightarrow \mu X$
Correct charge	70%	49%	94%
Wrong charge	0.5%	1.0%	1.5%

Physics performance

2x10^{20} pot's in ~5 years of SPS operation

Backgrounds with TP detector

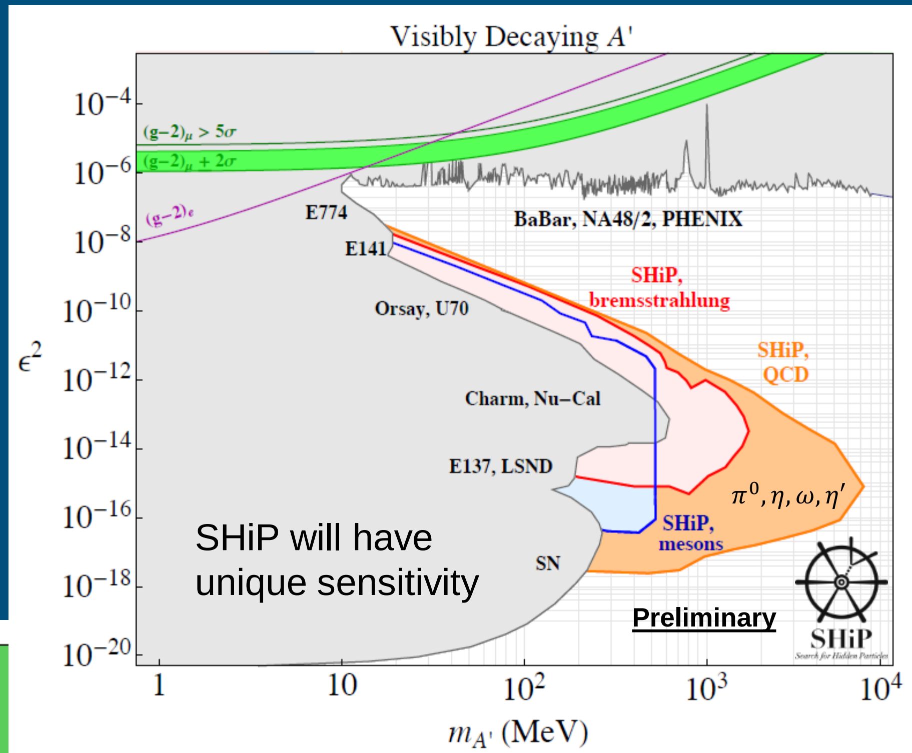
Background source	Decay modes
ν or μ + nucleon $\rightarrow X + K_L$	$K_L \rightarrow \pi e \nu, \pi \mu \nu, \pi^+\pi^-, \pi^+\pi^-\pi^0$
ν or μ + nucleon $\rightarrow X + K_S$	$K_S \rightarrow \pi^0\pi^0, \pi^+\pi^-$
ν or μ + nucleon $\rightarrow X + \Lambda$	$\Lambda \rightarrow p\pi^-$
n or p + nucleon $\rightarrow X + K_L$, etc	as above

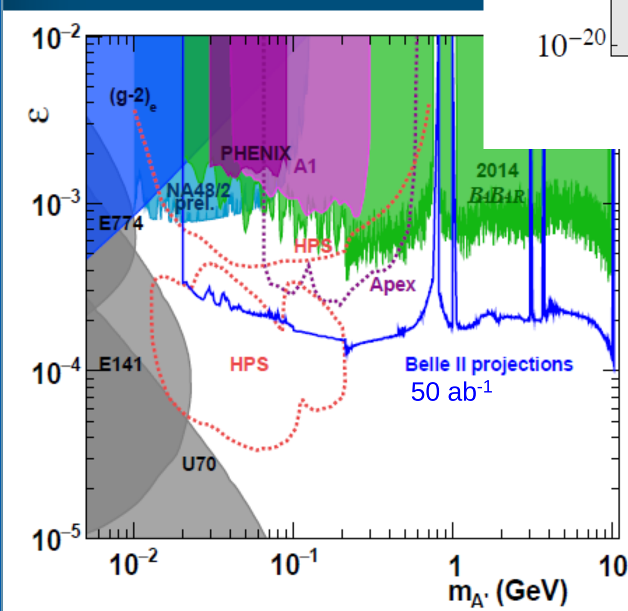


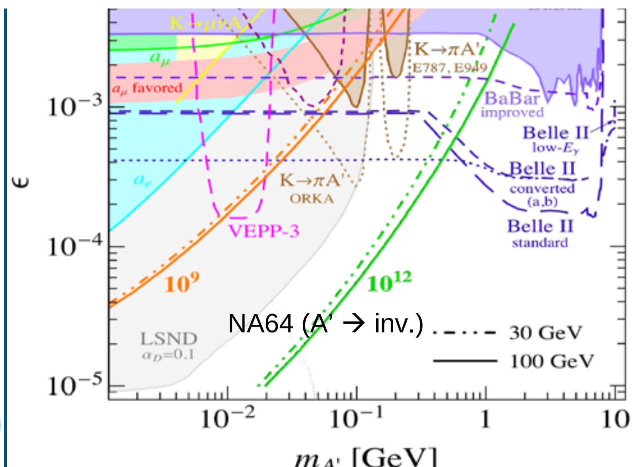
- <u>Background summary: no evidence for any irreducible background</u>
  - No events selected in MC ➔ Expected background UL @ 90% CL

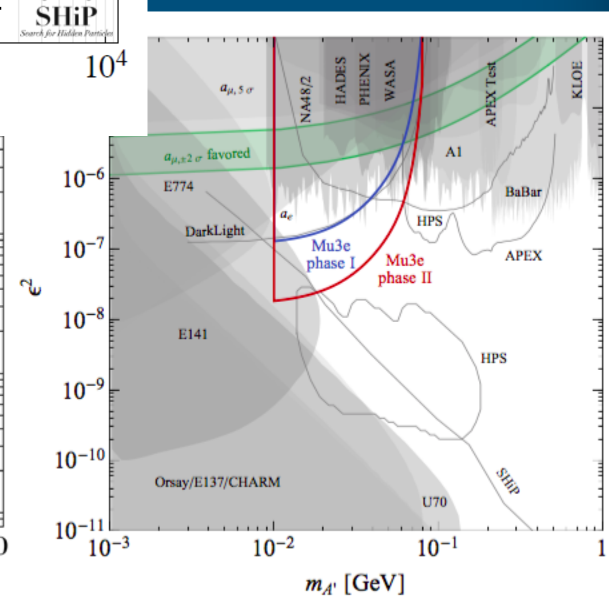
Background source	Stat. weight	Expected background (UL 90% CL)
ν-induced		
$2.0 < p < 4.0$ GeV/c	1.4	1.6
$4.0 < p < 10.0$ GeV/c	2.5	0.9
$p > 10$ GeV/c	3.0	0.8
$\overline{\nu}$-induced		
$2.0 < p < 4.0$ GeV/c	2.4	1.0
$4.0 < p < 10.0$ GeV/c	2.8	0.8
$p > 10$ GeV/c	6.8	0.3
Muon inelastic	0.5	4.6
Muon combinatorial	–	<0.1
Cosmics		
$p < 100$ GeV/c	2.0	1.2
$p > 100$ GeV/c	1600	0.002

Prospects for dark photons

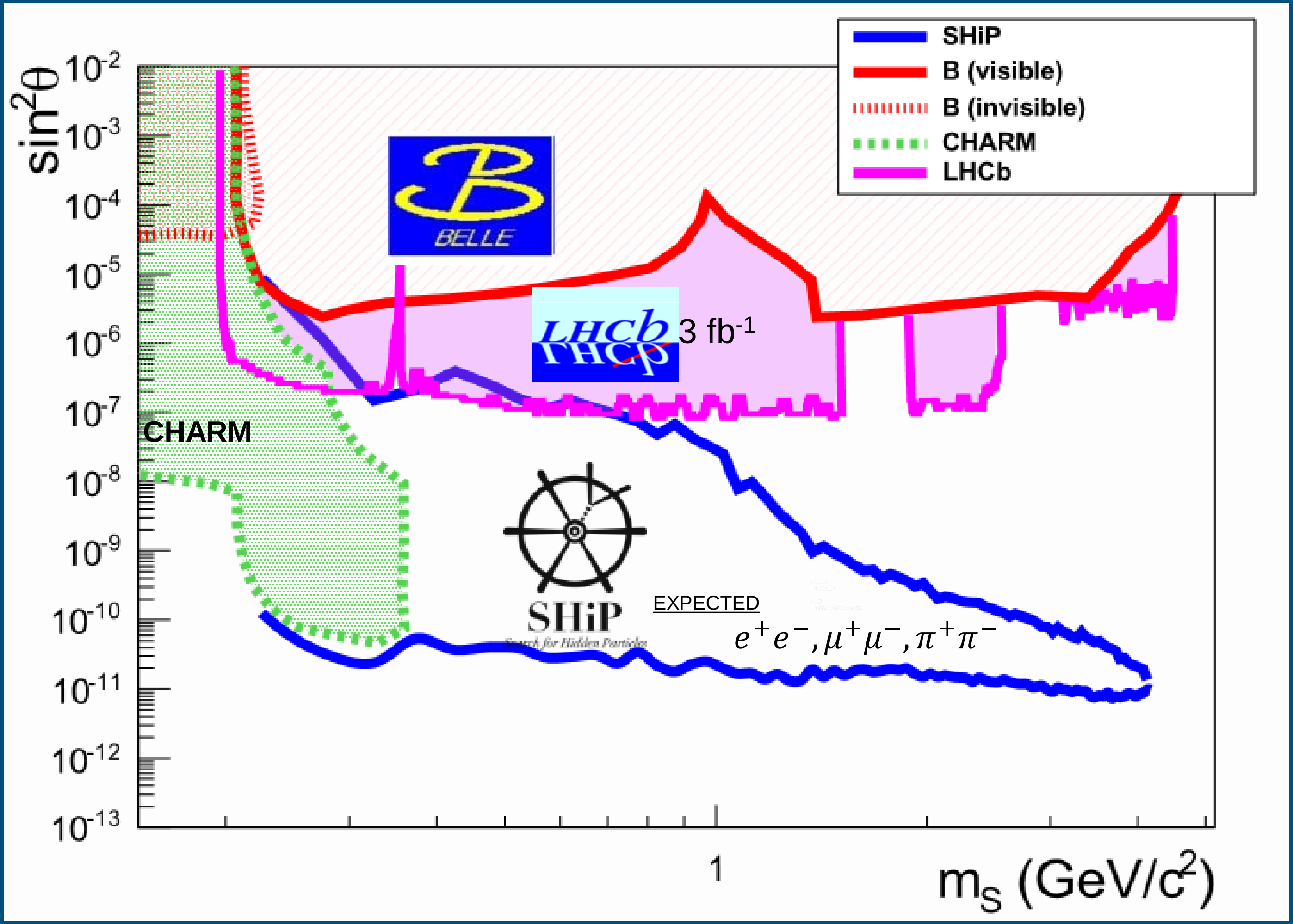








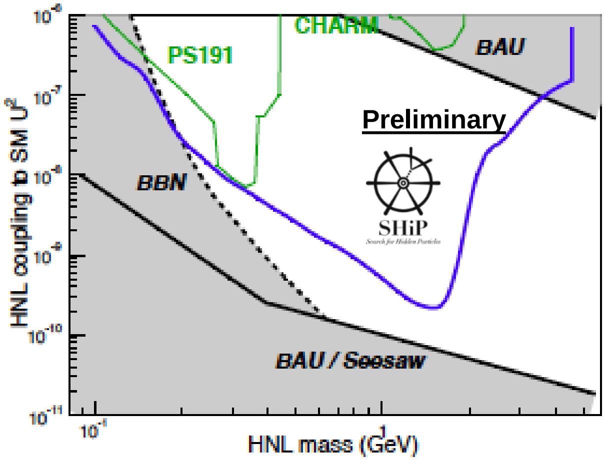
Prospects for hidden scalars



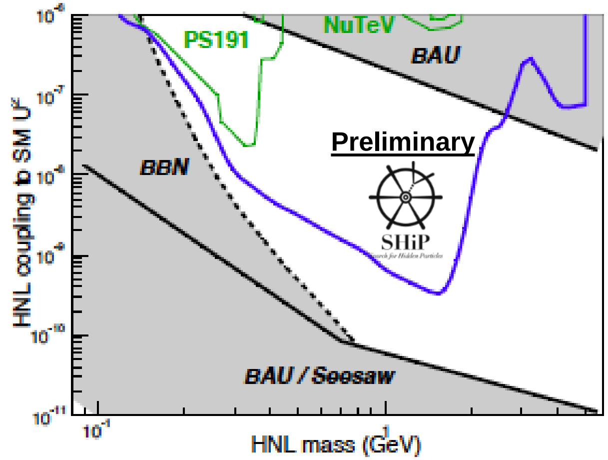
Prospects for HNL

- Visible decays = At least two tracks crossing the spectrometer
  - Ex. For m_N = 1 GeV with $\mathcal{U}^2$= 10^{-8} and $\mathcal{BR}(N \to \mu\pi)$ = 20%, expect ~330 signal events

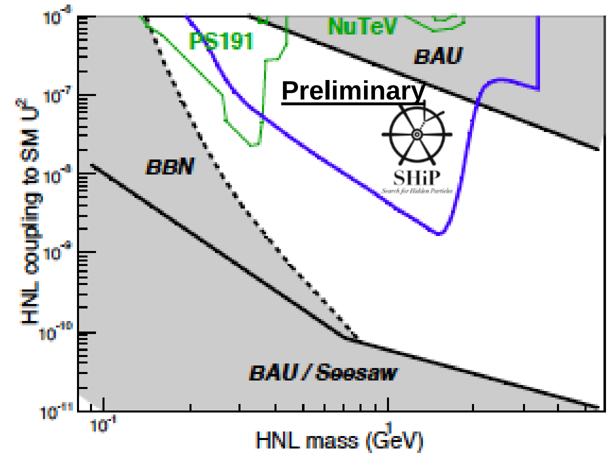
$U_e^2 : U_\mu^2 : U_\tau^2 \sim 52:1:1$, inverted hierarchy



$U_e^2 : U_\mu^2 : U_\tau^2 \sim 1:16:3.8$, normal hierarchy

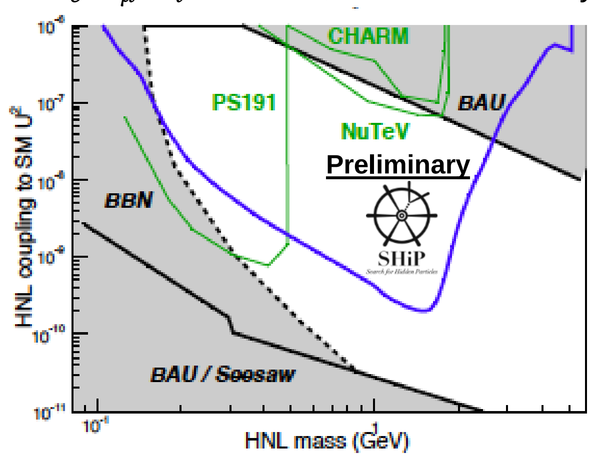


$U_e^2 : U_\mu^2 : U_\tau^2 \sim 0.061:1:4.3$, normal hierarchy

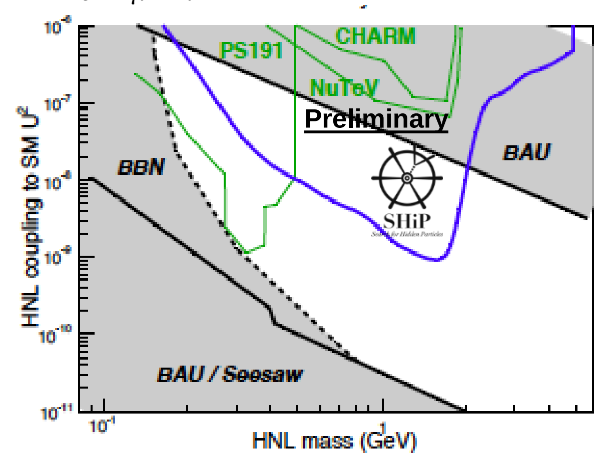


Scenarios for which baryogenesis was numerically proven

$U_e^2 : U_\mu^2 : U_\tau^2 \sim 48:1:1$, inverted hierarchy

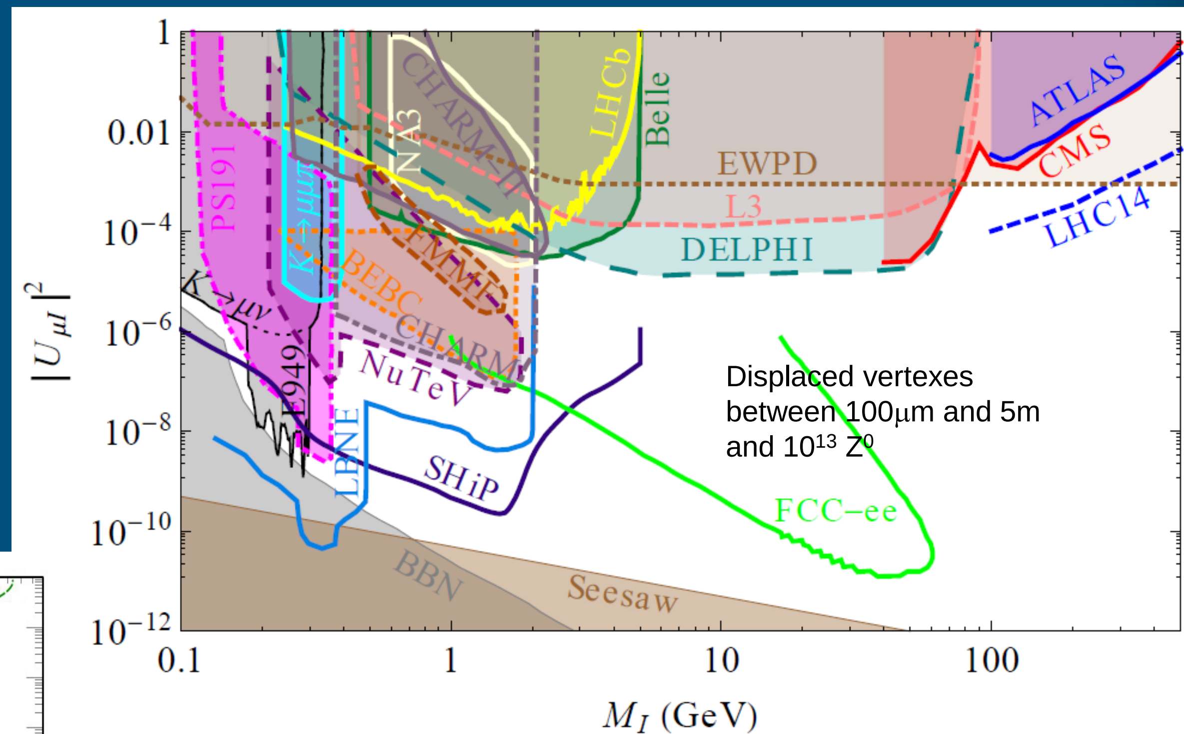


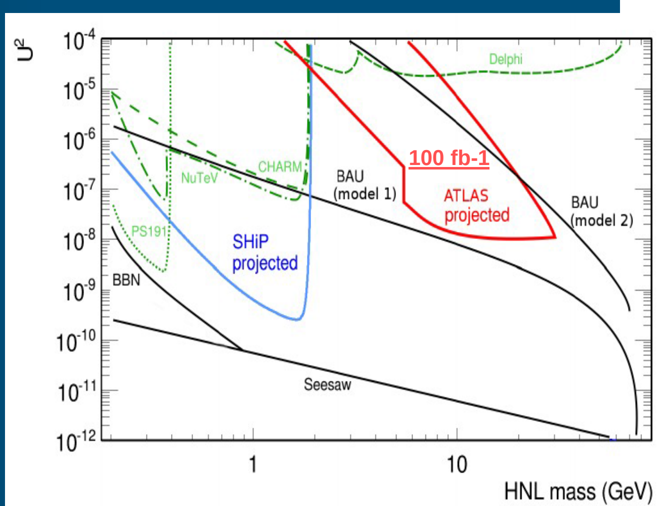
$U_e^2 : U_\mu^2 : U_\tau^2 \sim 1:11:11$, normal hierarchy



Prospects for HNLs

- BELLE-2 using $B \rightarrow XlN$, where $N \rightarrow l\pi$ l = e,mu, and X reconstructed using missing mass may go well below 10^{-4} in $0.5<M_N<5$ GeV
- LHCb, ATLAS/CMS
- HNLs at FCC 2 – 90 GeV
  - FCC-ee/CEPC , H-factory
  - FCC-hh: 100 TeV pp
- ILC >100 GeV





ν_τ-physics in brief

SM Physics: Prospects for ν_τ (ν_e, ν_μ)

- Most elusive particle in SM
  - DONUT experiment 9 events with 1.5 expected background
  - OPERA experiment 5 events from $\nu_\mu \rightarrow \nu_\tau$ oscillation
  - ➔ No distinction between ν_τ and $\bar{\nu}_\tau$

➔ Expected interactions in SHiP with 6-tonne target

	<E> (GeV)	Beam dump	<E> (GeV)	Neutrino target	<E> (GeV)	CC DIS interactions
N_{ν_e}	3	$2.1 \cdot 10^{17}$	28	$3.6 \cdot 10^{15}$	46	$2.5 \cdot 10^{5}$
N_{ν_μ}	1.4	$4.4 \cdot 10^{18}$	8	$5.2 \cdot 10^{16}$	29	$1.7 \cdot 10^{6}$
N_{ν_τ}	9	$2.8 \cdot 10^{15}$	28	$1.4 \cdot 10^{14}$	59	$6.7 \cdot 10^{3}$
$N_{\bar{\nu}_e}$	4	$1.6 \cdot 10^{17}$	27	$2.7 \cdot 10^{15}$	46	$9.0 \cdot 10^{4}$
$N_{\bar{\nu}_\mu}$	1.5	$2.8 \cdot 10^{18}$	8	$4.0 \cdot 10^{16}$	28	$6.7 \cdot 10^{5}$
$N_{\bar{\nu}_\tau}$	8	$2.8 \cdot 10^{15}$	26	$1.4 \cdot 10^{14}$	58	$3.4 \cdot 10^{3}$

➔ Reconstructed events and charm background events

decay channel	ν_τ			$\bar{\nu}_\tau$		
	N^{exp}	N^{bg}	R	N^{exp}	N^{bg}	R
$\tau \rightarrow \mu$	570	30	19	290	140	2
$\tau \rightarrow h$	990	80	12	500	380	1.3
$\tau \rightarrow 3h$	210	30	7	110	140	0.8
Total	1770	140	13	900	660	1.4

➔ Neutrino induced charm events

	Expected events
ν_μ	$6.8 \cdot 10^4$
ν_e	$1.5 \cdot 10^4$
$\bar{\nu}_\mu$	$2.7 \cdot 10^4$
$\bar{\nu}_e$	$5.4 \cdot 10^3$
Total	$1.1 \cdot 10^5$

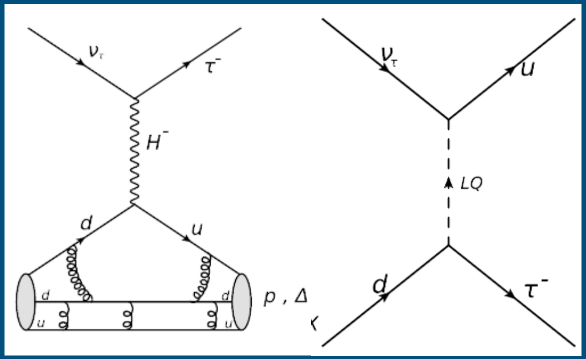
SM Physics: Prospects for ν_τ (ν_e, ν_μ)

1. First observation of ν_τ interaction
2. Measurement of ν_τ and $\bar{\nu}_\tau$ cross-sections

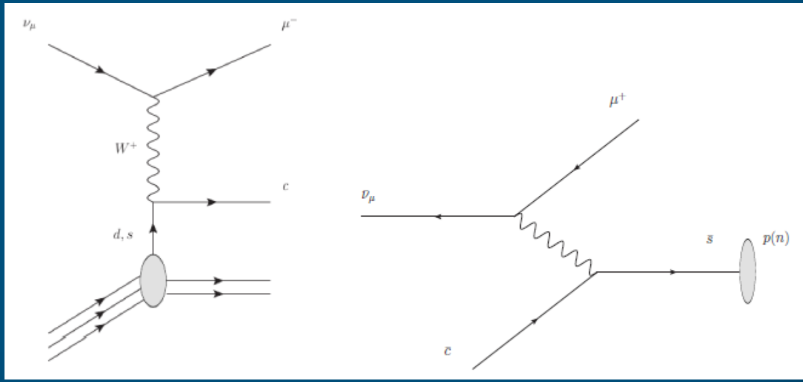
$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})\right]F_2 \pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5\Bigg),$$

➔ Allow extraction of F4 and F5 structure functions from charged current neutrino-nucleon DIS

➔ Beyond SM

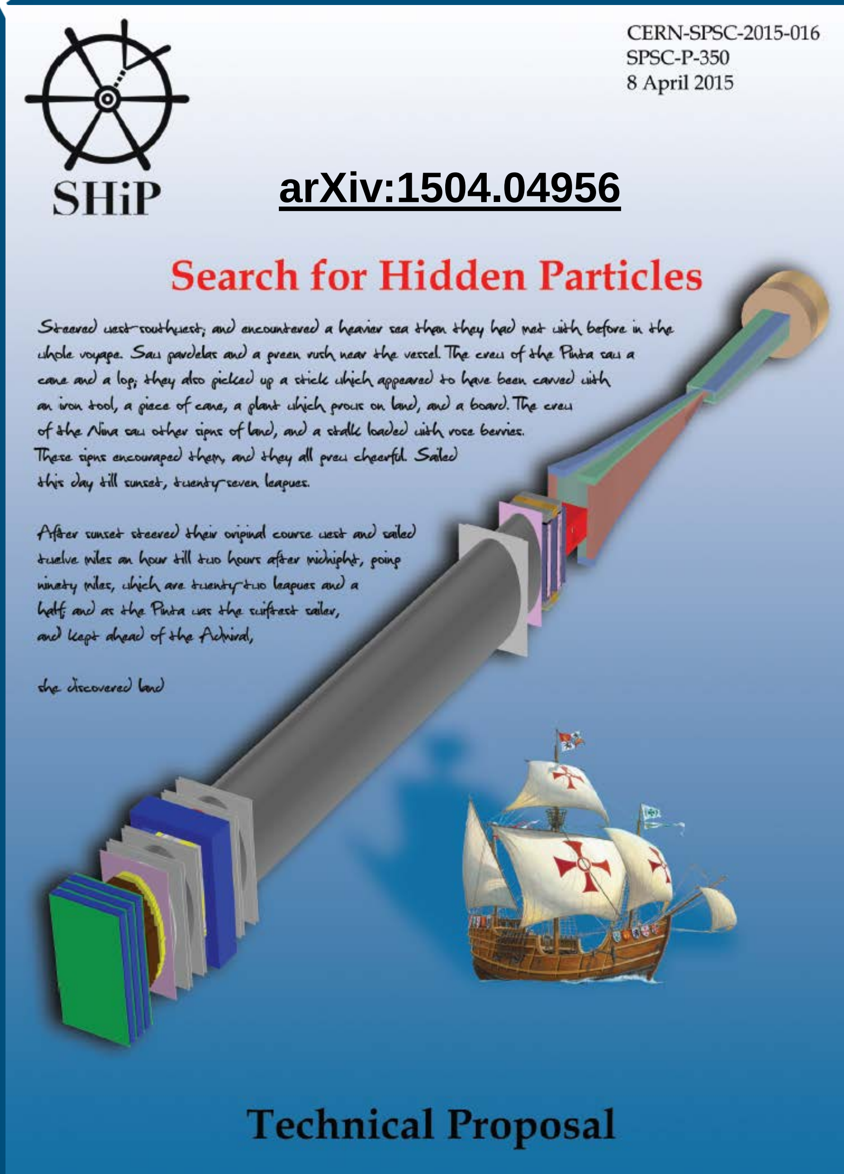


3. ν_e cross section at high energy
4. Testing strange quark content of nucleon through charm production



5. Normalization of hidden particle search
6. LNU

SHiP Technical Proposal


CERN-SPSC-2015-016
SPSC-P-350
8 April 2015

SHiP

arXiv:1504.04956

Search for Hidden Particles

Steered west-southwest, and encountered a heavier sea than they had met with before in the whole voyage. Saw pardelas and a green rush near the vessel. The crew of the Pinta saw a cane and a log; they also picked up a stick which appeared to have been carved with an iron tool, a piece of cane, a plant which grows on land, and a board. The crew of the Nina saw other signs of land, and a stalk loaded with rose berries. These signs encouraged them, and they all grew cheerful. Sailed this day till sunset, twenty-seven leagues.

After sunset steered their original course west and sailed twelve miles an hour till two hours after midnight, going ninety miles, which are twenty-two leagues and a half; and as the Pinta was the swiftest sailer, and kept ahead of the Admiral,

she discovered land

Technical Proposal

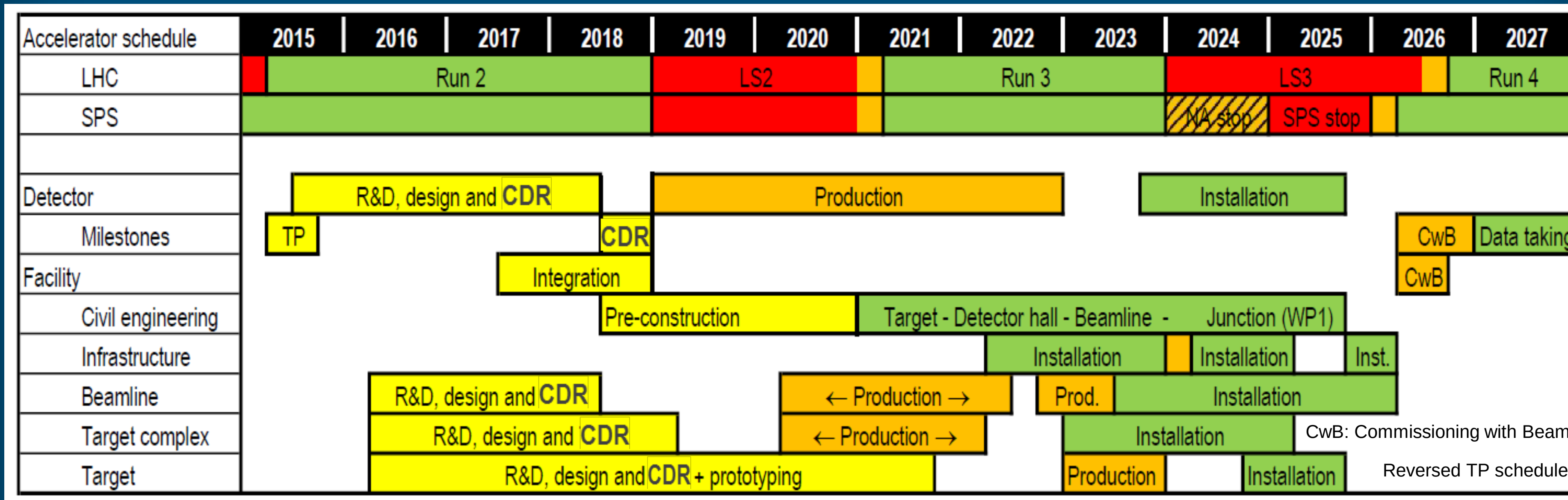
- Technical Proposal
  - 243 members from 45 institutes in 14 countries
  - 250 pages

  + 200 pages of complementary documents outlining beam, target, RP, and civil engineering by CERN task force

- TP Addendum to SPSC Oct. 2015
  - Updates on backgrounds, sensitivity, comparison with other facilities, and schedule and resources

Organization and schedule

Project schedule



- 10 years from TP to data taking
  - Schedule optimized for minimal interference with operation of North Area
    - ➔ Preparation of facility in four clear and separate work packages (junction cavern, beam line, target complex, and detector hall)
    - ➔ Use of Long Shutdown 3 for junction cavern and first short section of SHiP beam line
  - Comprehensive Design Study 2016 – 2018: Starting now! ➔ Update of European HEP strategy 2018
  - Construction / production 2021 –
  - Data taking 2026 (start of LHC Run 4)

Project organization: Collaboration April 2015

- SHiP Collaboration at the time of TP:
  - 250 members from 45 institutes in 14 countries
  - Admission of several institutes pending

Current commitments for preparation of TP and CDR

Component	Countries	Institutes
Beamline and target	CERN	CERN
Infrastructure	CERN	CERN
Muon shield	UK	RAL, Imperial College, Warwick
HS vacuum vessel	Russia	NRC KI
Straw tracker	Russia, CERN	JINR, MEPhI, PNPI, CERN
HS spectrometer magnet		
ECAL	France, Italy, Russia	ITEP, Orsay, IHEP, INFN-Bologna
HCAL	Italy, Russia, Sweden	ITEP, IHEP, INFN-Bologna, Stockholm
Muon	Italy, Russia	INFN-Bologna, INFN-Cagliari, INFN-Lab. Naz. Frascati,
		INFN-Ferrara, INR RAS, MEPhi
Surrouding background tagger	Germany, Russia	Berlin, LPNHE, MEPhI
Timing detector and upstream veto	France, Italy, Russia, Switzerland	Zurich, Geneva, INFN-Cagliari, Orsay, LPNHE
Tau neutrino emulsion target	Italy, Japan, Russia, Turkey	INFN-Naples, INFN-Bari, INFN-Lab. Naz. Gran Sasso,
		Nagoya, Nihon, Aichi, Kobe, Moscow SU,
		Lebedev, Toho, Middle East Technical University, Ankara
Tau neutrino tracker (GEM)	Italy, Russia	NRC KI, INFN-Lab. Naz. Frascati
Tau neutrino detector magnet	Italy	INFN-Lab. Naz. Frascati, INFN-Bari, INFN-Naples,
		INFN-Roma
Tau neutrino tracking (RPC)	Italy	INFN-Lab. Naz. Frascati, INFN-Bari,
		INFN-Lab. Naz. Gran Sasso, INFN-Naples, INFN-Roma
Tau neutrino tracker (drift tubes)	Germany	Hamburg
Online computing	Denmark, Russia, Sweden, UK, CERN	Niels Bohr, Uppsala, UCL, YSDA, LPHNE, CERN
Offline computing	Russia, CERN	YSDA, CERN
MC simulation	Bulgaria, Chile, Germany, Italy, Russia,	Sofia, INFN-Cagliari, INFN-Lab. Naz. Frascati,
	Switzerland, Turkey, UK, Ukraine,	INFN-Napoli, Zurich, Geneva and EPFL Lausanne,
	USA, CERN	Valparaiso, Berlin, PNPI, NRC KI, SINP MSU, MEPhI,
		Middle East Technical University, Ankara, Bristol, YSDA,
		Imperial College, Florida, Kyiv, CERN

Conclusion

- *Bright future for Dark Sector*
  - Very much increased interested for Hidden Sector after LHC Run 1
- SHiP is a GP experiment for HS exploration in largely unexplored domain
  - Also unique opportunity for ν_τ physics, direct Dark Matter search, …
- Facility and physics case based on the current injector complex and SPS
  - 2×10^{20} at 400 GeV in 5 nominal years by "inheriting" CNGS share of the SPS beam time from 2026
  - Yield SHiP@CERN / FNAL (Bkg=0) : HNLs: 1.5x / Dark photons: ~1x / Dark scalar: 400x / ν_τ : 7x
  - JPARC charm production 1/200 (Dark photons: ~1x)
- SHiP complements the current NP searches at energy and intensity frontier
- Technical Proposal and Physics Proposal submitted in April 2015

➔ Next phase: Requested to produce Comprehensive Design 2016 – 2018

➔ Input to update of European HEP strategy 2018 - 2019

ありがとうございました！

Spare slides

SPS Committee review

- Technical Proposal and Physics Proposal submitted April 2015
  - ➔ 9 months review with SPSC

Official conclusion from SPSC

*The SPSC **has reviewed** the proposal for "A Facility to Search for Hidden Particles (SHiP) at the CERN SPS" (Technical Proposal P-350 and Physics case P-350-ADD-1), submitted in April 2015 following an earlier submission of the Expression of Interest EoI-010 in October 2013. The review included several lists of questions sent to the proponents, which were all answered including submission of a proposal addendum P-350-ADD-2 in October 2015.*

*In the review process the Committee **was impressed** by the dedication of the SHiP proponents and their responsiveness to the Committee's requests. In particular significant progress has been made since the EoI, along the lines of the SPSC112 recommendations, including optimisation of the proton beam dump design, broadening of the physics case and adaptation of the SHiP scheduling to external constraints. The CERN SPS offers a unique opportunity for the proposed programme and the SHiP proponents have the potential strength to build the proposed detector setup.*

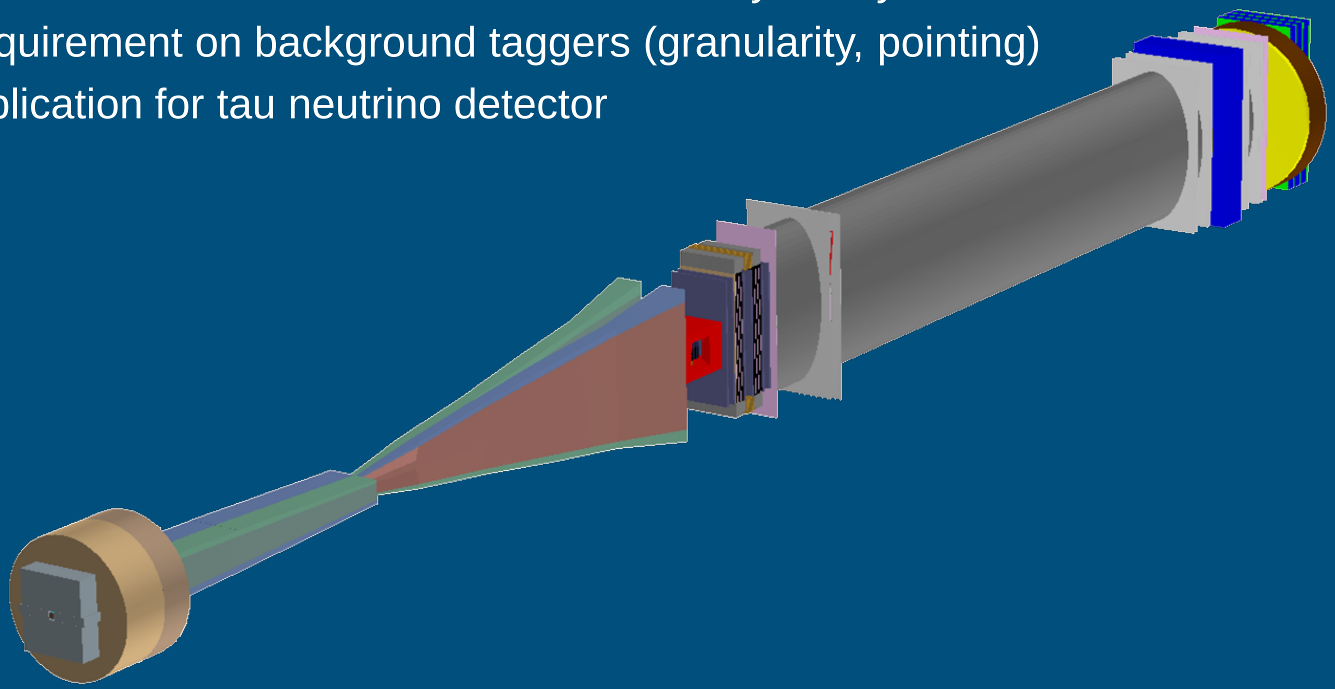
The main physics motivation of SHiP is to explore the domain of hidden particles, searching in particular for new scalar, fermionic and vector particles. These would be produced in a proton beam dump at 400 GeV, either directly or from decays of charm or beauty particles. The experiment would be sensitive to a hitherto unexplored region of parameter space, spanning masses from a few hundred MeV to a few GeV and over two orders of magnitude in squared couplings. The main experimental signature involves two charged decay tracks, and will be complemented by decays to neutral particles. The experiment is also proposed to be equipped with an emulsion target, which would allow for unprecedented tau neutrino and antineutrino measurements and valuable QCD studies. Furthermore it would extend the hidden sector search to scattering of dark matter particles. The facility could accommodate additional detectors extending the range of dark matter searches. The SPSC supports the motivation for the search for hidden particles, which will explore a domain of interest for many open questions in particle physics and cosmology, and acknowledges the interest of the measurements foreseen in the neutrino sector. SHiP could therefore constitute a key part of the CERN Fixed Target programme in the HL-LHC era.

*The SPSC **supports** the updated SHiP schedule, which takes into account the HL-LHC preparation constraints during LS2, and defers any significant civil engineering investments for SHiP to the period following full approval of SHiP. The SPSC **notes** that, in this updated schedule, the time scale for the SHiP comprehensive design study, required for a final decision, coincides with the expected revision of the EU HEP strategy. The Committee **also notes** the plans of the incoming CERN Management to set up a working group to prepare the future of the CERN Fixed Target programme after LS2, as input to the next EU strategy update. In this context the SPSC **recommends** that the SHiP proponents proceed with the preparation of a Comprehensive Design Report (CDR) , and that this preparation be made in close contact with the planned Fixed Target working group.*

*Preparation of the CDR should include further optimisation of the beam dump facility in the direction of a multipurpose area, test beams of detector prototypes where needed, detailed simulations of the detector response to all signal and background signatures, further theoretical studies of expected signals and comparisons with alternative search programmes. The Committee **encourages** the proponents to define a programme of measurements concerning production of charm in a SHiP-like target, important for normalisation purposes. The SPSC **also encourages** the proponents to further explore the potential benefit of inputs from the ongoing NA62 experiment to strengthen the experimental evaluation of SHiP backgrounds and systematics. The resources needed for the preparation of* the SHiP CDR in the coming years should be secured within a MoU between CERN and the SHiP proponents' institutes.

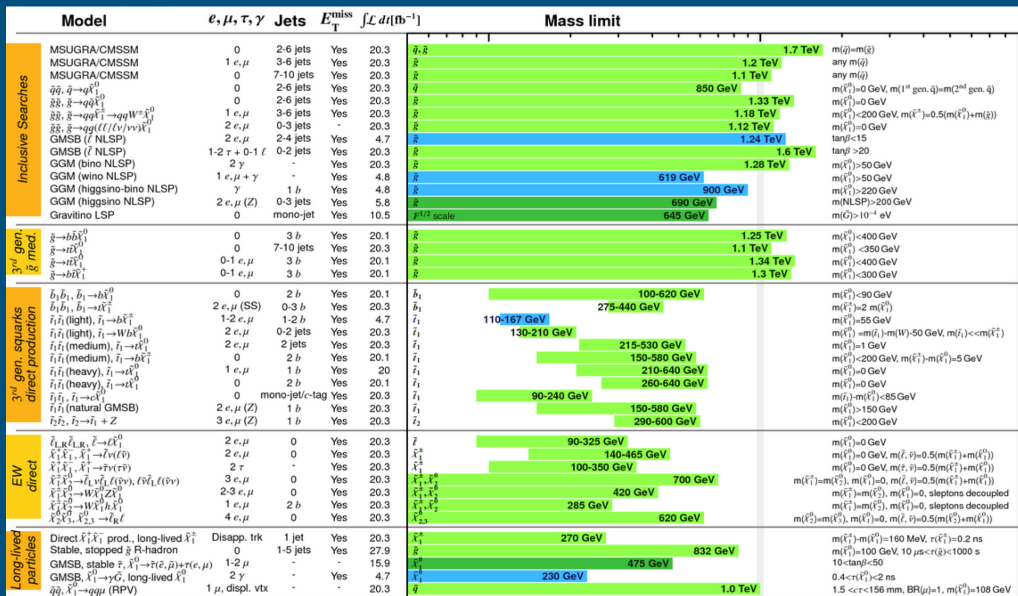
New phase (face) of SHiP

- Begin with re-optimization by revisiting
  - Muon shield including superconducting option, magnetization of hadron stopper
  - Evacuation of decay volume including the option of helium balloon
  - Shape of decay volume, conical to get closer
  - Implications for the spectrometer tracker (resolution) – detector technologies
  - Extended PID for neutral modes, three body decays etc – detector technology
  - Requirement on background taggers (granularity, pointing)
  - Implication for tau neutrino detector
  - …

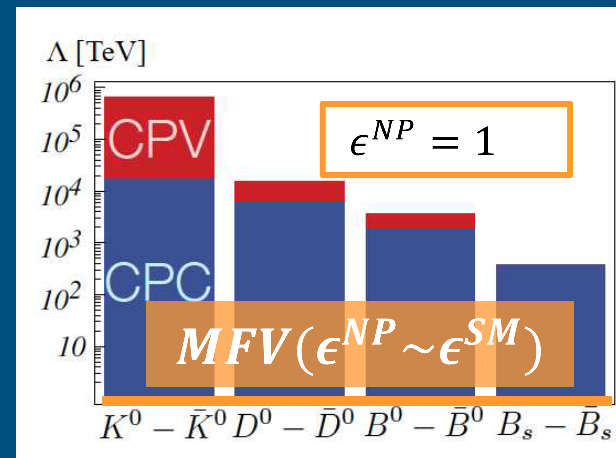


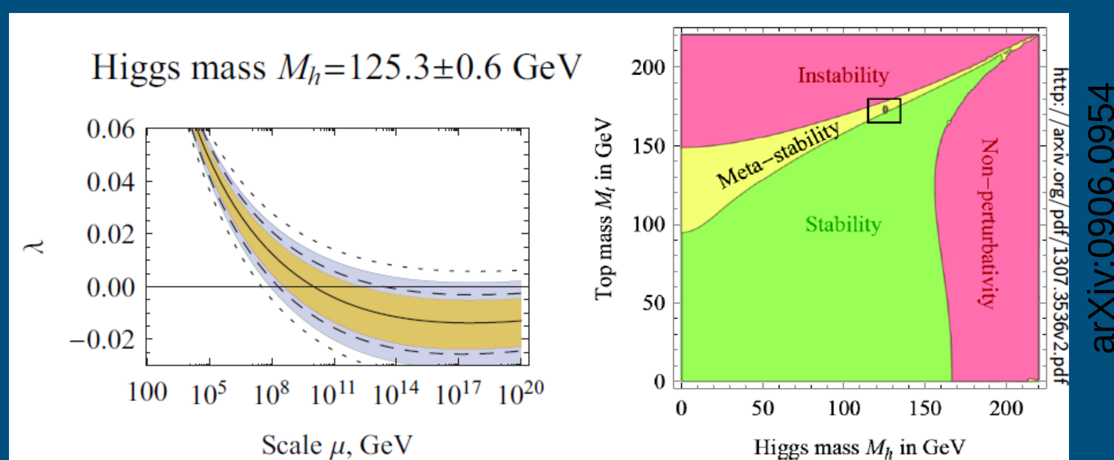
- Prototyping in 2017 and conclusions with updated sensitivities and cost in 2018

Current Physics Scenario



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \delta C[\frac{\epsilon^{NP}}{\Lambda_{NP}^2}]$$





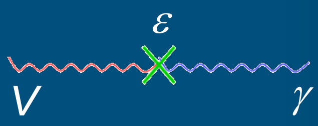
We expect(ed?) TeV scale new physics with sizable couplings but….
…no tangible evidence for new physics and no hint of the scale!

Phenomenology of some groups of physics models for SHiP

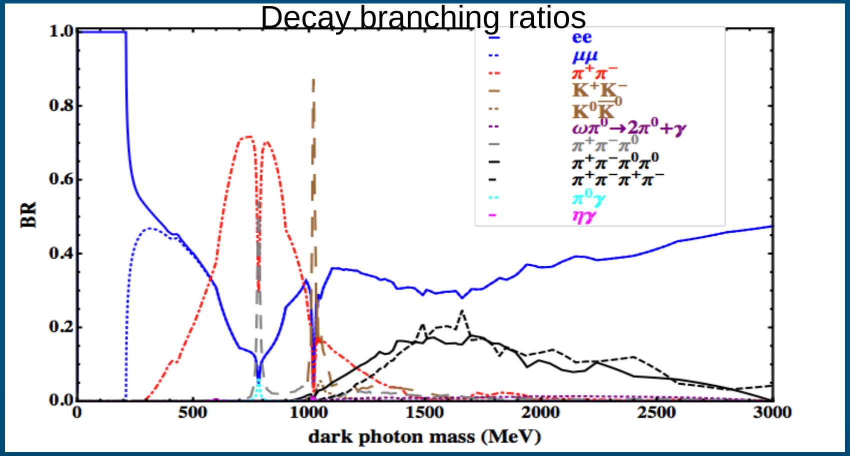
D = GeV²: Vector portal

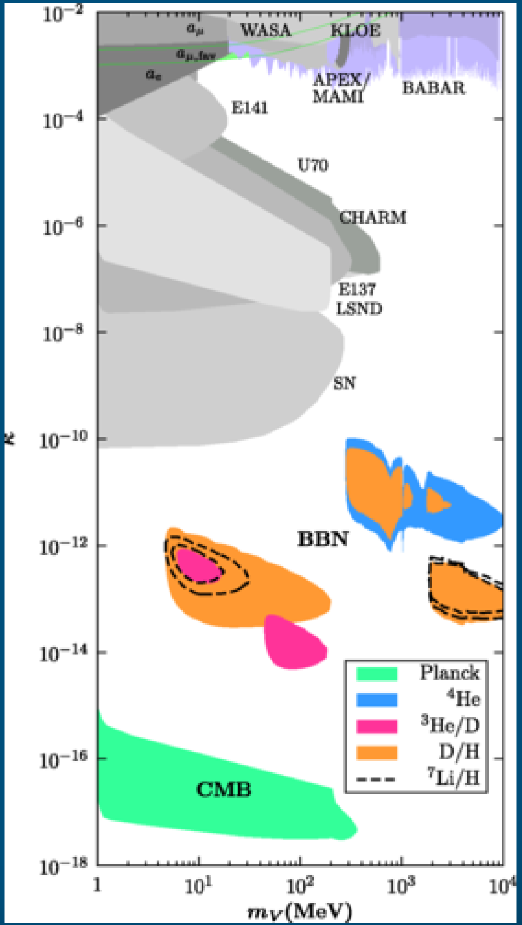
- Massive dark (hidden, secluded, para-) photon
  - Motivated in part by idea of "mirror world" restoring symmetry between left and right and constituting dark matter, positron excess, g-2 anomaly, …
  - SM portal through kinetic mixing with massive dark/secluded/paraphoton V

$$\mathcal{L} = \frac{1}{2}\varepsilon F_{\mu\nu}^{SM} V_{HS}^{\mu\nu}$$, also mixing with Z



- Predominant dark photon production at SPS
  - Proton bremsstrahlung from quasi-elastic $pp \rightarrow ppV$
  - Meson decays $(\pi^0, \eta,\ \omega,\ \eta', \ldots)$
  - Direct QCD production $q\bar{\bar{q}} \rightarrow V, qg \rightarrow Vq$
  - Lifetime limit from BBN: $\tau_\gamma < 0.1s$
- Dark photon decays
  - Visible $e^+e^-, \mu^+\mu^-, q\bar{q}\ (\pi^+\pi^-, \ldots), \ldots$
  - Invisible $\chi\bar{\bar{\chi}},\ m_\chi < \frac{1}{2}m_V$, where χ hidden sector particle





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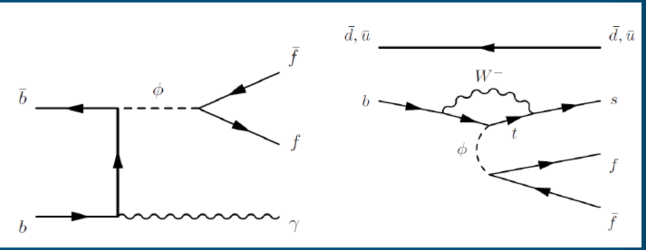
D=GeV²: Scalar portal

- **Singlet dark scalar *S***
  - ➔ Motivated by possibility of inflaton in accordance with Planck and BICEP measurements, giving mass to Higgs boson and right-handed neutrinos, dark phase transitions BAU, Dark Matter, dark Naturalness…,etc
  - ➔ SM portal through mass mixing with the SM Higgs: λ

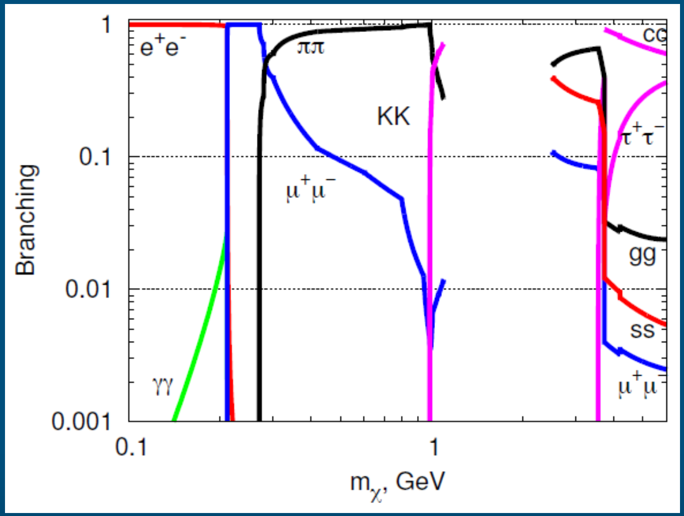
$$\mathcal{L} = (gS + \lambda S^2)H^\dagger H$$

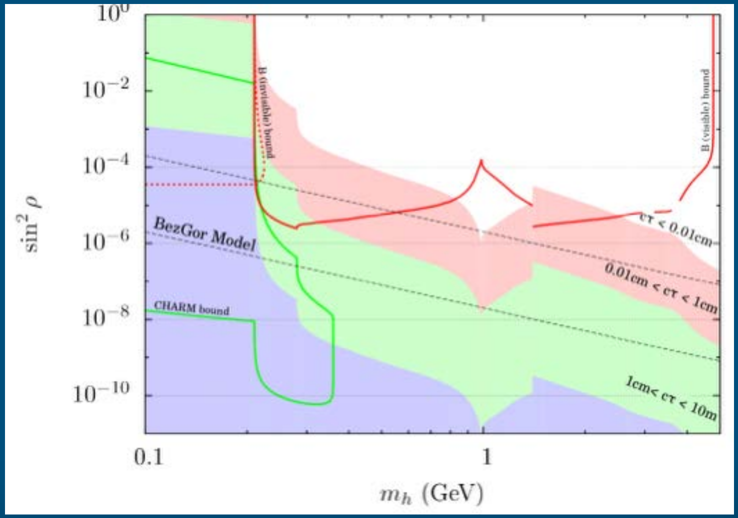
$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\rho & -\sin\rho \\ \sin\rho & \cos\rho \end{pmatrix} \begin{pmatrix} \phi_0' \\ S' \end{pmatrix}$$

- Production
  - Direct $p + target \rightarrow X + S$
  - Meson decays e.g. $B \rightarrow KS,\ K \rightarrow \pi S$
    - Production in D decays suppressed, i.e. $(m_t^2|V_{ts}^* V_{tb}|)^2/(m_b^2|V_{cb}^* V_{ub}|)^2$
  - ➔ Lifetime $\tau \propto \sin^{-2}\rho$



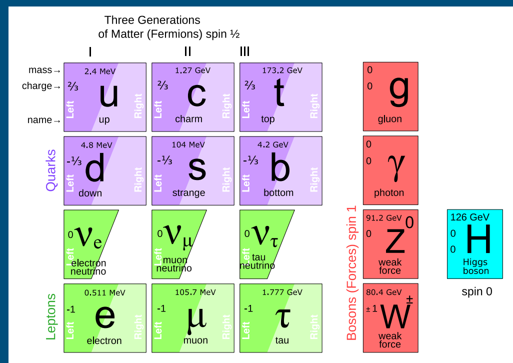
- Decay modes:

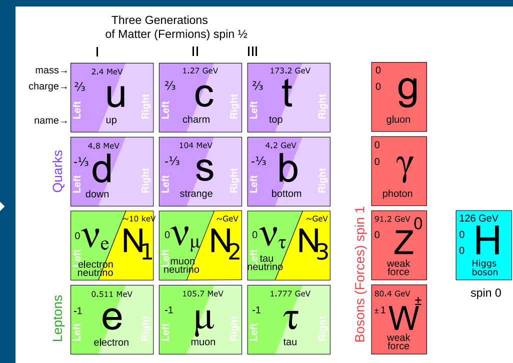




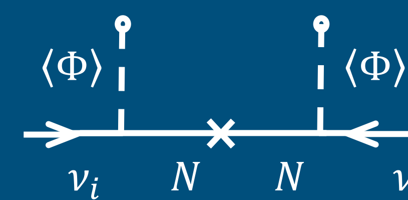
D=GeV$^{5/2}$: Neutrino portal

- Extension of SM with one massive right handed Majorana/Dirac neutrino per family
  - Motivated by neutrino oscillation, baryon asymmetry and Dark Matter

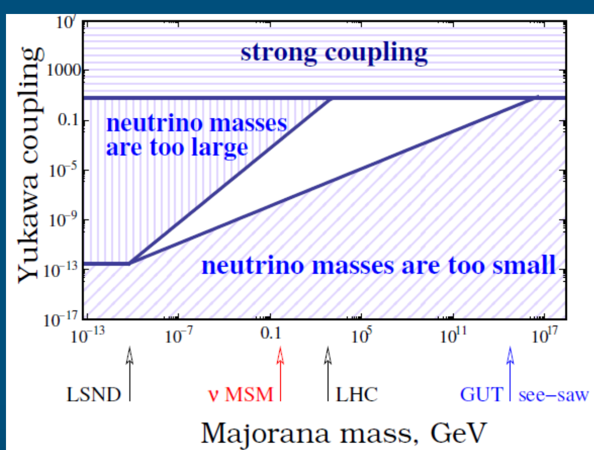




- $Y_{I\ell}H^{\dagger}\bar{N}_I L_\ell$ lepton flavour violating term results in mixing between N_I and SM active neutrinos
  - ➔ Oscillations in the mass-basis and CP violation
  - ➔ Type I See-Saw with Majorana $m^R >> m_D (= Y_{I\ell}v)$



- Four "popular" N mass ranges:



	N mass	ν masses	eV ν anoma–lies	BAU	DM	M_H stability	direct search	experi–ment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

arXiv:1204.5379

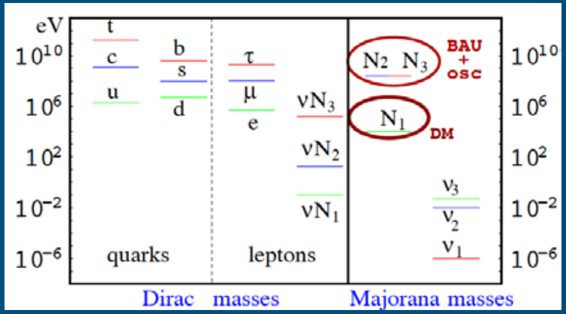
Ex. : HNLs in νMSM (Asaka, Shaposhnikov)

Role of N_1 with a mass of $\mathcal{O}$(keV)
➔ Dark Matter

Role of N_2 and N_3 with a mass of $\mathcal{O}(m_q/m_{l^\pm})$ (100 MeV – GeV):
➔ Neutrino oscillations and mass, and BAU

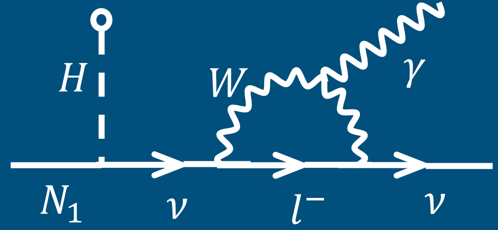
➔ Assumption that N_I are $\mathcal{O}(m_q/m_l)$: No new energy scale!

- $Y_{I\ell} = \mathcal{O}\left(\frac{\sqrt{m_{atm} m_I^R}}{v}\right) \sim 10^{-8} \quad (m^R = 1\ GeV, m_\nu = 0.05\ eV)$
- $\mathcal{U}^2 \sim 10^{-11}$

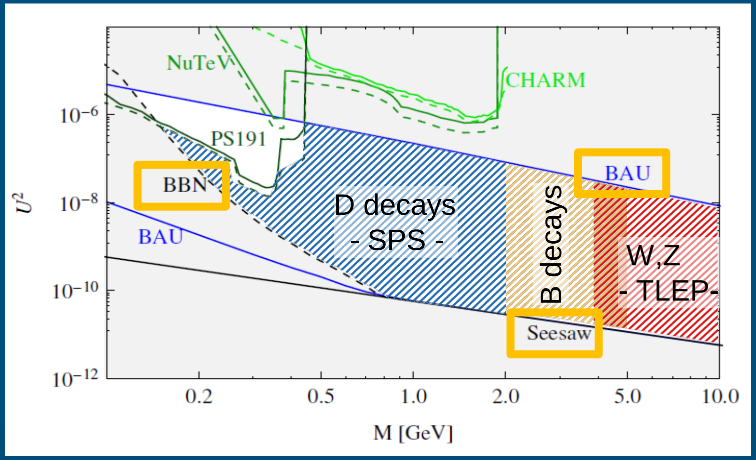


Current limits on N_2 and N_3

N_1 Subdominant radiative decay



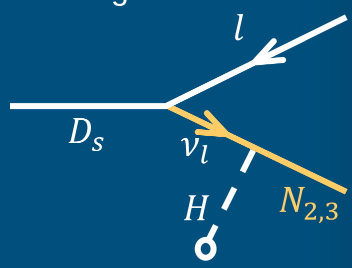
$$E_\gamma = \frac{M_{N_1} c^2}{2}$$



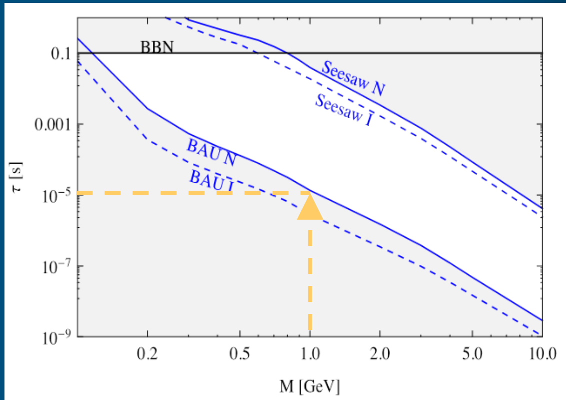
HNL production and decay

- Predominant production in mixing with active neutrino from leptonic/semi-leptonic weak decays of heavy mesons
  - $D_s \to lN,\ (\tau \to X\nu_\tau)$ $U^2_{e,\mu,\tau}$ and $N_N \leq M(D_s) - m_l,\ (N_N \leq M(\tau) - M(X))$
  - $D \to lKN$ $U^2_{e,\mu}$ and $N_N \leq M(D_s) - m_l$
  - $B_{(s)} \to D_{(s)} lN$ $U^2_{e,\mu,\tau}$ and $N_N \leq M\left(B_{(s)}\right) - M(D_{(s)}) - m_l$
  - $B \to lN \ \ (B \to l\pi N)$ $U^2_{e,\mu,\tau}$ and $N_N \leq M(B) - m_l$ $,Br \propto V^2_{ub}/V^2_{cb}$
  - ➔ Branching ratios $\mathcal{O}(10^{-7} - 10^{-8})$

E.g.

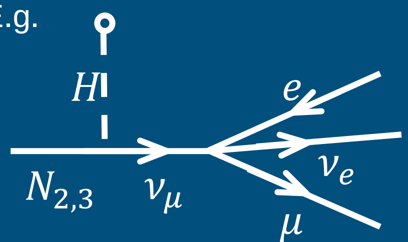


- Very weak HNL-active neutrino mixing → $N_{2,3}$ much longer lived than SM particles
  - ➔ Typical lifetimes > 10 μs for $M_{N_{2,3}} \sim 1\ GeV$ → Decay distance $\mathcal{O}(km)$



- Decay modes
  - $N \to h^0\nu,\ with\ h^0 = \pi^0, \rho^0, \eta\ \ , \eta'$
  - $N \to h^\pm l^\mp,\ with\ h^\pm = \pi^\pm, \rho^\pm$
  - $N \to 3\nu$
  - $N \to l^\pm l^\mp \nu$

E.g.



- Total rate depend on $\mathcal{U}^2 = \sum_{\substack{I=2,3 \\ \ell=e,\mu,\tau}} |\mathcal{U}_{\ell I}|^2$
  - ➔ Relation between $\mathcal{U}_e{}^2, \mathcal{U}_\mu{}^2$ and $\mathcal{U}_\tau{}^2$ depends on flavour mixing

Decay mode	Branching ratio
$N_{2,3} \to \mu/e + \pi$	*0.1 - 50 %*
$N_{2,3} \to \mu^-/e^- + \rho^+$	*0.5 - 20 %*
$N_{2,3} \to \nu + \mu + e$	*1 - 10 %*

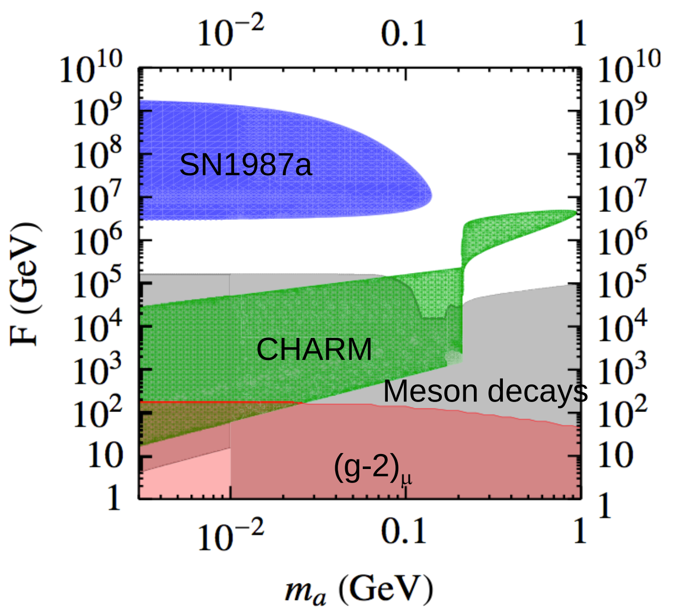
D=GeV^4: Axion portal

- Axion Like Particles, pseudo-scalars pNGB, axial vectors a
  - Appear in extended Higgs, SUSY breaking, motivated by coupling with dark sector, possibility of inflaton, etc
  - Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale F

    ➔ Couplings suppressed by the breaking scale *F* and masses are light $\sim\Lambda/F^2$
  - SM portal through mixing with gauge bosons and fermions

$$\mathcal{L} = \frac{a}{F} G_{\mu\nu}\tilde{G}^{\mu\nu}, \frac{\partial_\mu a}{F}\bar{\psi}\gamma_\mu\gamma_5\psi \text{ , etc}$$

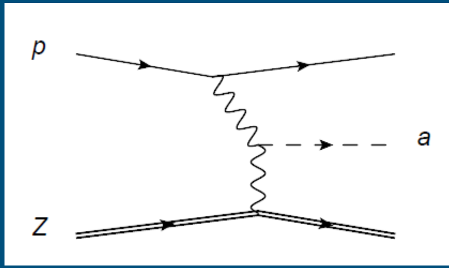
- Production
  - Resonant production from Drell-Yan photons
  - Production from mixing with pions and heavy meson decays
- Decays
  - Decays to $e^+e^-, \mu^+\mu^-$, hadrons above 1 GeV
  - Decays to photon pair

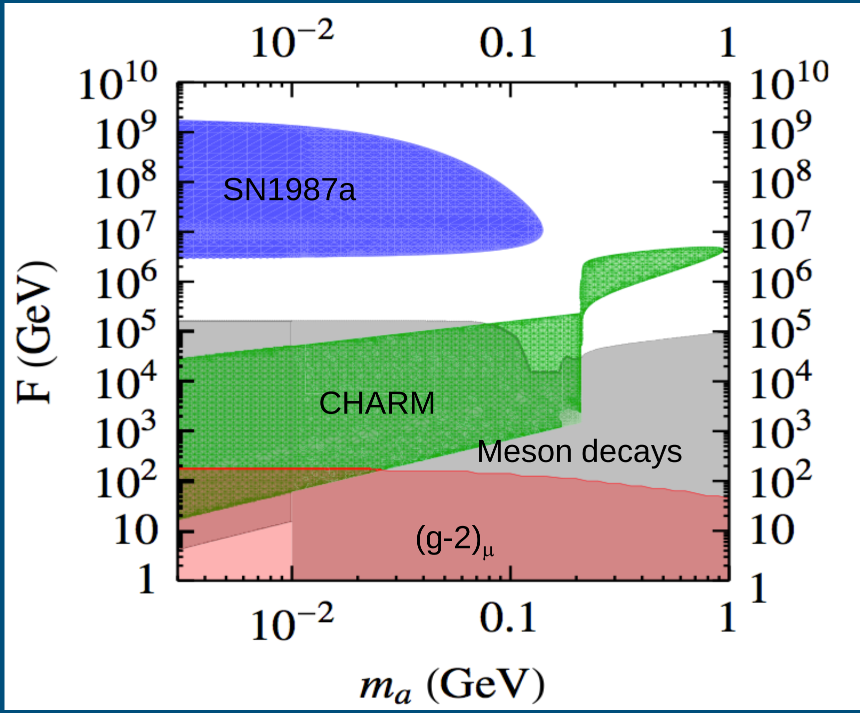


PRD 82,113008 (2010)

ALP searches

- Production:
  - Primakoff production, mixing with pions and heavy meson decays
  - $a \rightarrow \gamma\gamma, \mu^+\mu^-$





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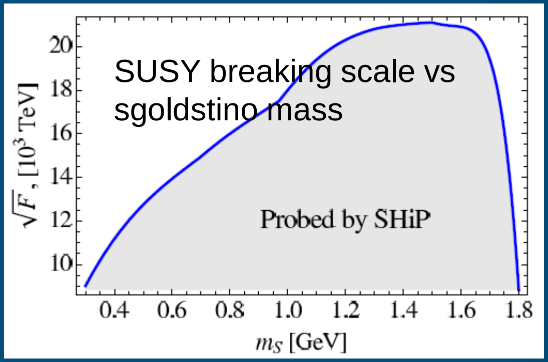
SUSY with light long-lived partners

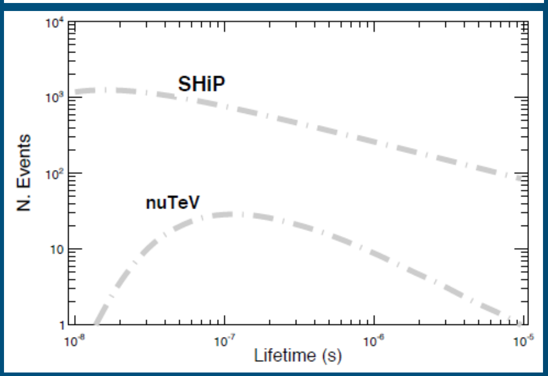
- The absence of SUSY below TeV and the relatively large Higgs mass leads to increasing electro-weak fine-tuning of the SUSY parameters
  - How to make SUSY natural?

  ➔ Lowering breaking scale $\Lambda_{SUSY} = \sqrt{F}$ in hidden sector to few TeV leads to different gravitino/goldstino and DM sectors ➔ light, possibly long-lived particles

- Sgoldstino S(P)
  - Massless at tree level but massive via loop corrections
  - Coupling e.g. $\mathcal{L}_{eff} \propto \frac{M_{\gamma\gamma}}{F} S F^{\mu\nu} F_{\mu\nu}$
  - Naturally light in no-scale SUGRA and GMSB
  - Direct production: gg fusion,
  - Indirect production: heavy hadron decays $D \rightarrow \pi S(\mathrm{P})$ $D_s \rightarrow K^+ S(P)$
  - Decay: $X \rightarrow \pi^+\pi^-, \pi^0\pi^0, l^+l^-, \gamma\gamma$



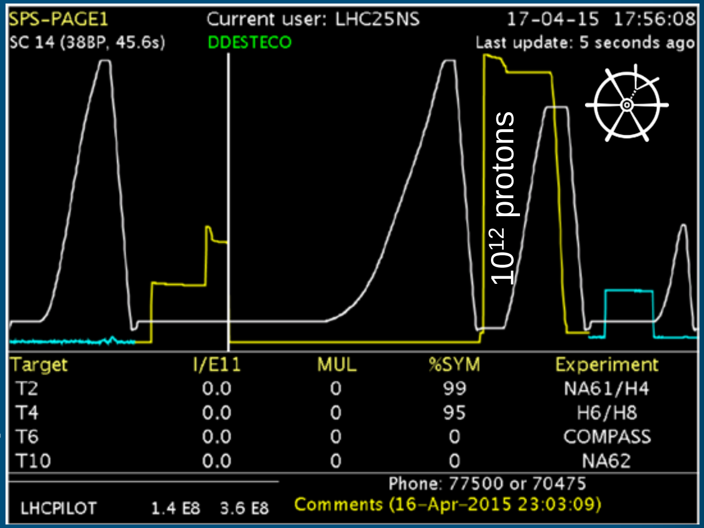
- Neutralino in R-Parity Violating SUSY
  - LSP can decay into SM particles
  - Light neutralino with long lifetime $\tau_{\tilde{\chi}} < 0.1s$ (BBN)
  - Production: heavy meson decays $D \rightarrow \nu\tilde{\chi}$, $D^{\pm} \rightarrow l^{\pm}\tilde{\chi}$
  - Decay: $\tilde{\chi} \rightarrow l^+l^-\nu$



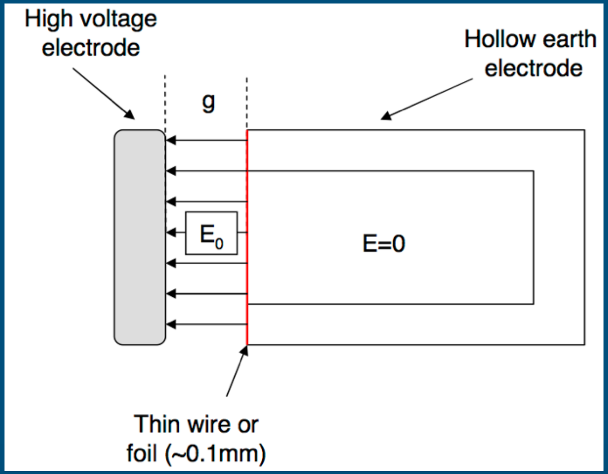
- Hidden Photinos, axinos and saxions….

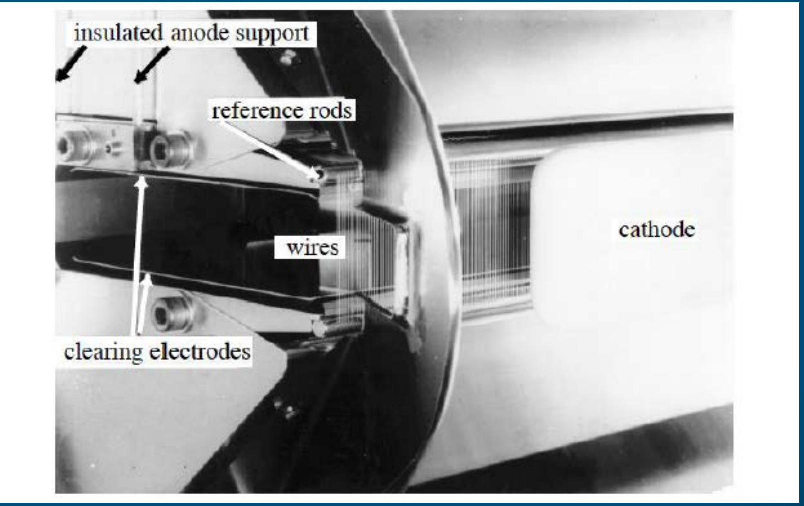
SPS 400 GeV beam extraction

- Use slow beam extraction as for NA, but 1 sec flat top
- SHiP cycle length is 7.2 s (note: CNGS cycle was 6 s)
- 4 10^{13} ppp is historical maximum for slow extraction
  - Unavoidable losses on septum concentrated in 1 second!
  - Expect 4×10^{11} protons per spill to hit wires: T → 800°C (operational limit is 1000°C)
  - Radioactivity, vacuum degradation, sparking, wire damage,…

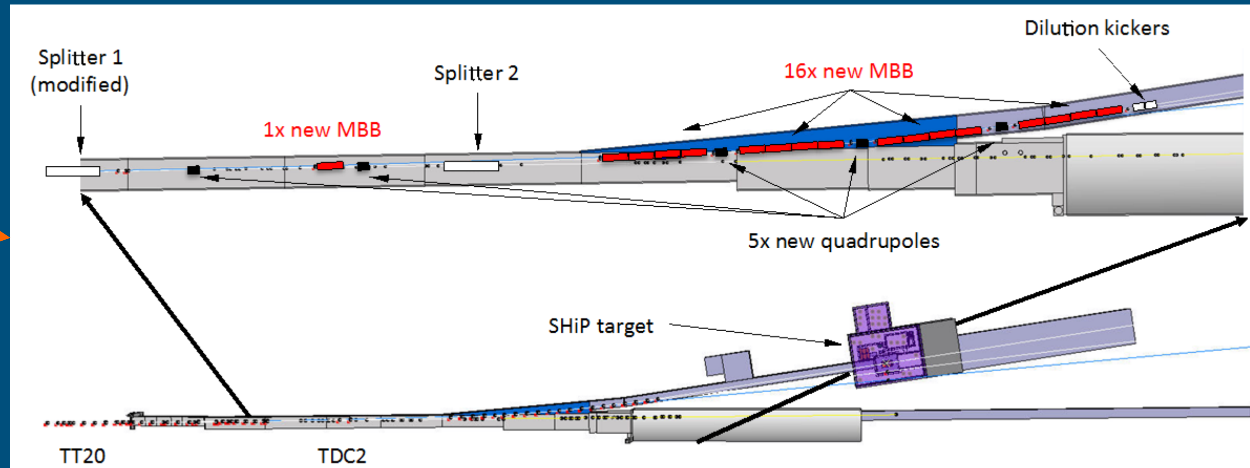


- Improvements needed
  - Instrumentation for optimal extraction and reproducibility
  - Novel methods for beam extraction?





SHiP beam line

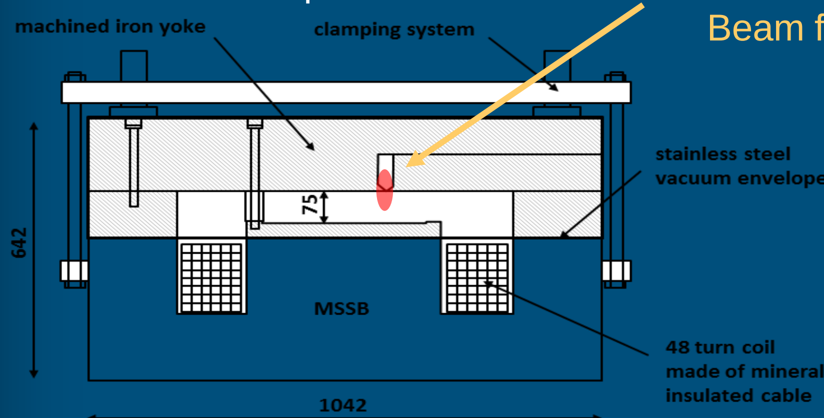


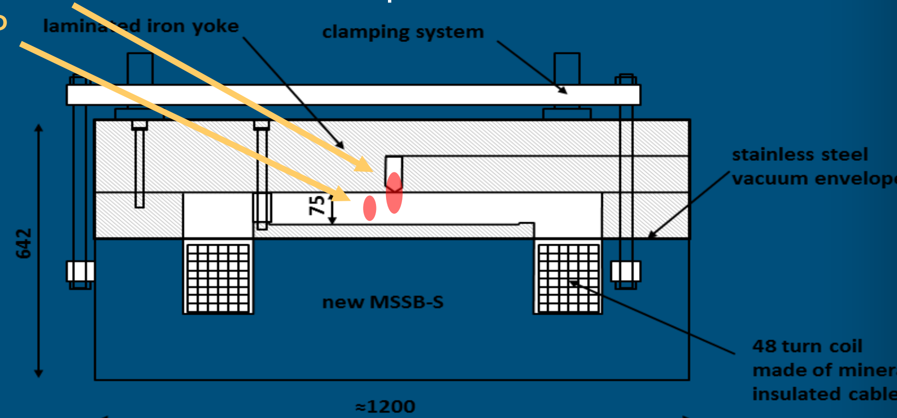
- Current splitter 1 magnet to be replaced with "three-way" splitter
  - Bipolar, larger horizontal aperture and laminated yoke

Old splitter

Beam for T6 as now
Beam for SHiP

New splitter

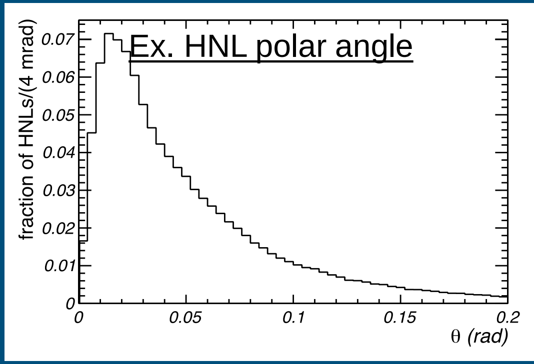


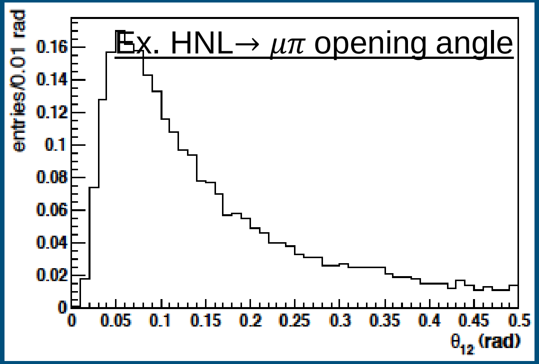


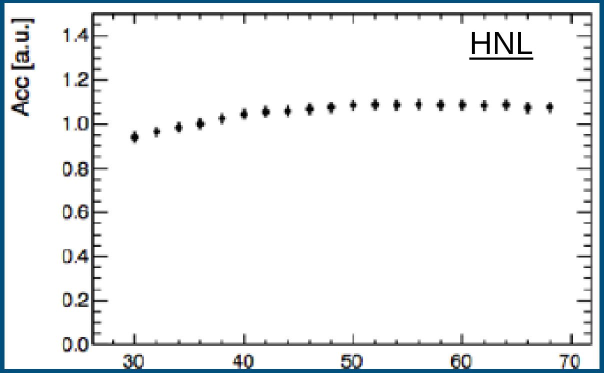
- Beam sweeping according to Archimedean spiral to reduce power density on target

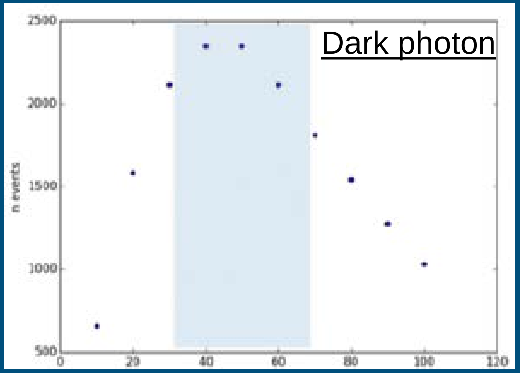
HS detector optimization

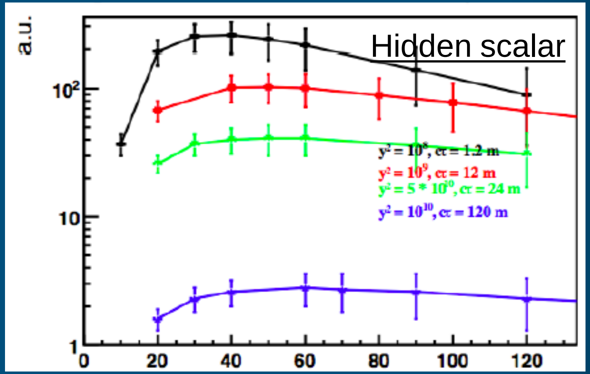
- Optimization of geometrical acceptance for a given E_{beam} and Φ_{beam}
  - Hidden particle lifetime (~flat for longlived)
  - Hidden particle production angles (~distance and transversal size)
  - Hidden particle decay opening angle (~length and transversal size)
  - Muon flux (~distance and acceptable occupancy)
  - Background (~detector time and spatial resolution)
  - Evacuation in decay volume / technically feasible size ~ W:5m x H:10m



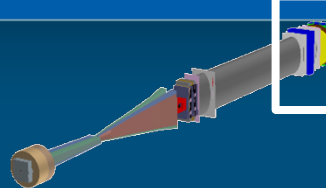








➔ Acceptance saturates ~40m – 50m

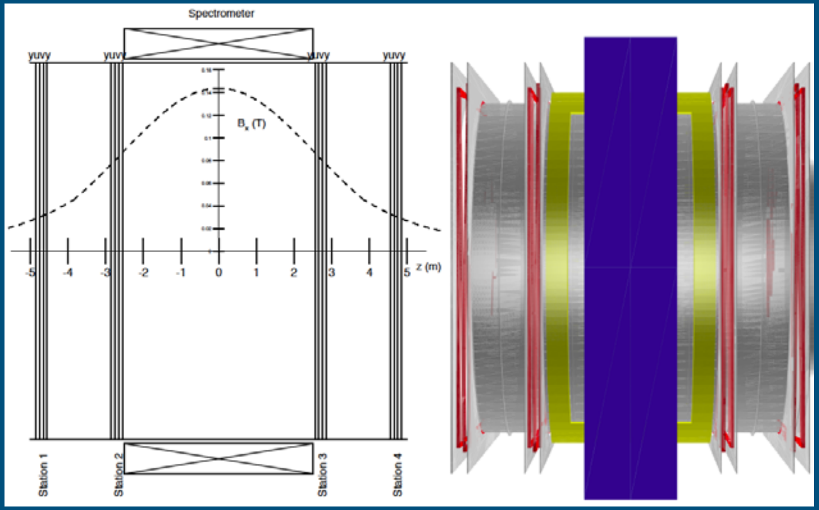


HS tracking system

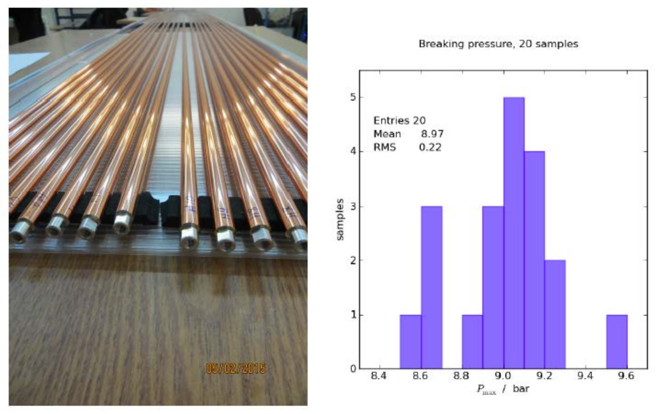
- NA62-like straw detector

Parameter	Value
Straw	
Length of a straw	5 m
Outer straw diameter	9.83 mm
Straw wall (PET, Cu, Au)	
PET foil thickness	36 μm
Cu coating thickness	50 nm
Au coating thickness	20 nm
Wire (Au-plated Tungsten)	
diameter	30 μm
Straw arrangement	
Number of straws in one layer	568
Number of layers per plane	2
Straw pitch in one layer	17.6 mm
Y extent of one plane	$\sim$ 10 m
Y offset between straws of layer 1&2	8.8 mm
Z shift from layer 1 to 2	11 mm
Number of planes per view	2
Y offset between plane 1&2	4.4 mm
Z shift from plane 1 to 2	26 mm
Z shift from view to view	100 mm
Straw station	
Number of views per station	4 (Y-U-V-Y)
Stereo angle of layers in a view Y,U,V	0, 5, -5 degrees
Z envelope of one station	$\sim$ 34 cm
Number of straws in one station	9088
Straw tracker	
Number of stations	4
Z shift from station 1 to 2 (3 to 4)	2 m
Z shift from station 2 to 3	5 m
Number of straws in total	36352

Horizontal orientation of 5m straws



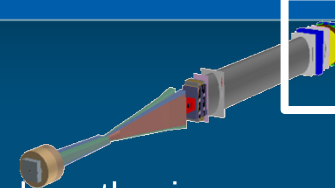
First production of 5m straws at JINR



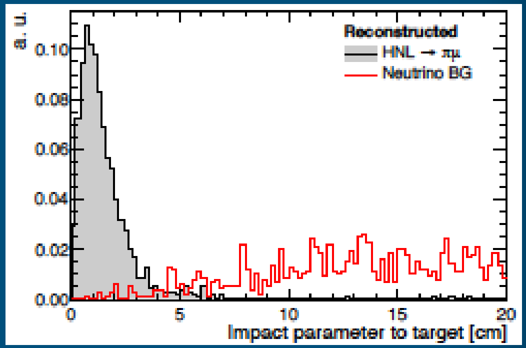
- Straws in test beam 2016
  - Study sagging effects and compensation
  - Read out of signal, attenuation / two-sided readout
- Upstream straw veto may be based on same technology

JINR Dubna (NA62, SHiP): Straws
St Petersburg (CMS, SHiP): Infra

Tracker performance



- Critical tasks: Decay vertex, DOCA, χ^2, impact parameter at target of decay hypothesis, …

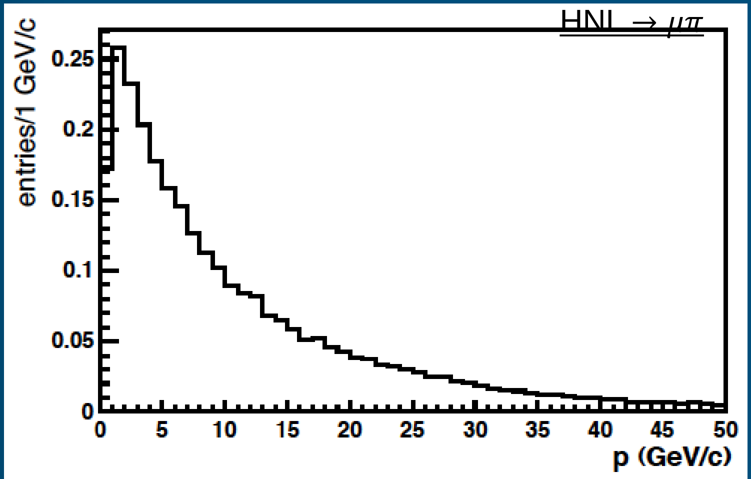


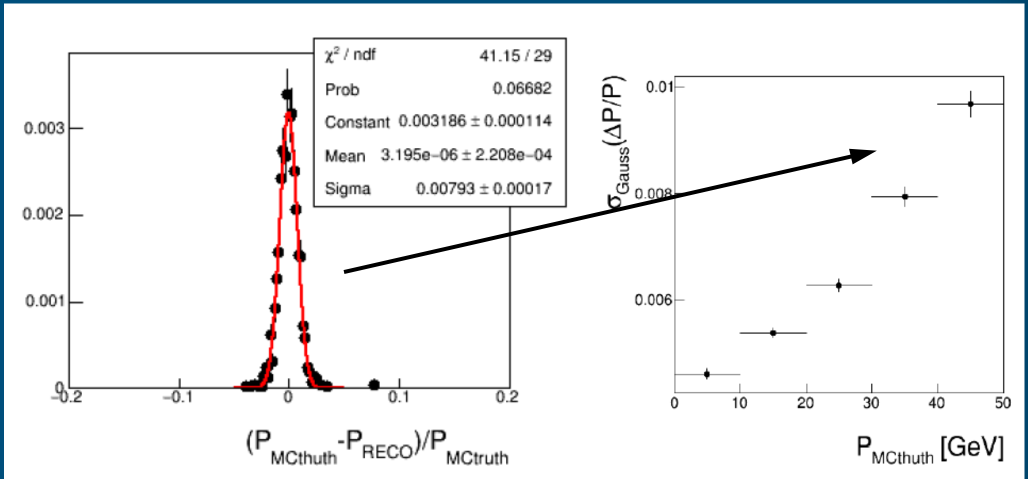
- Assuming NA62 parameters
  - Material budget per station 0.5% X_0
  - Position resolution 120 μm per straw, 8 hits per station on average

➔ $\left(\frac{\Delta p}{p}\right)^2 \sim [0.49\%]^2 + [0.022\%/(GeV/c)]^2 \times p^2$

➔ Momentum resolution is dominated by multiple scattering below 20 GeV/c

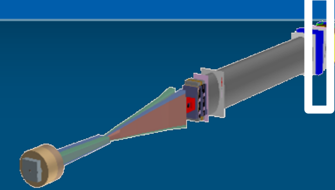
(For HNL → $\mu\pi$, 75% of both decay products have p<20 GeV/c



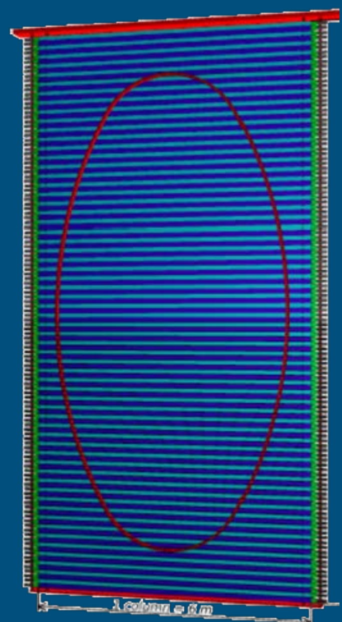


- Vertex resolution (also driven by multiple scattering and $\frac{\Delta p}{p}$) : $\sigma_{xy} \sim \mathcal{O}(mm)$, $\sigma_z \sim \mathcal{O}(cm)$

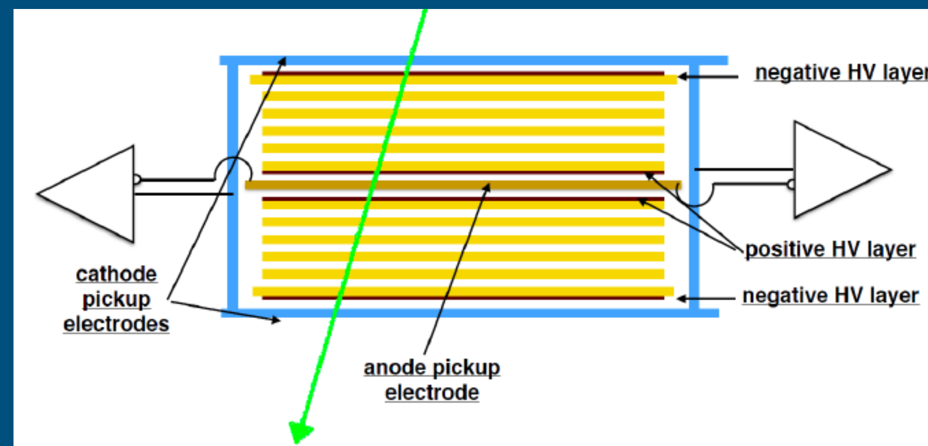
Timing detector



- Critical task: Coincidence of decay products
- Two options: scintillating bars (NA61/SHINE, COMPASS) and MRPC (ALICE)



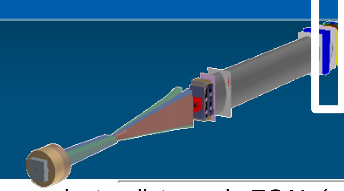
120 bars x 11cm (1cm overlap) = 12m



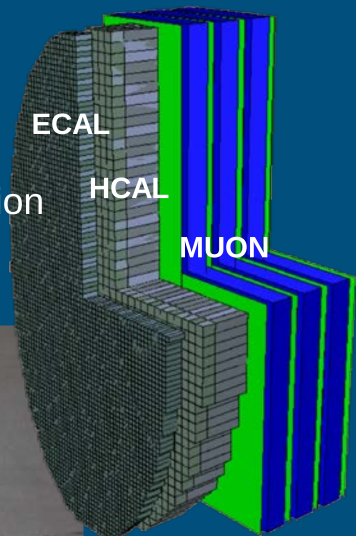
120 cm long strips, 3 cm wide pitch
Actual intrinsic time resolution ~20ps

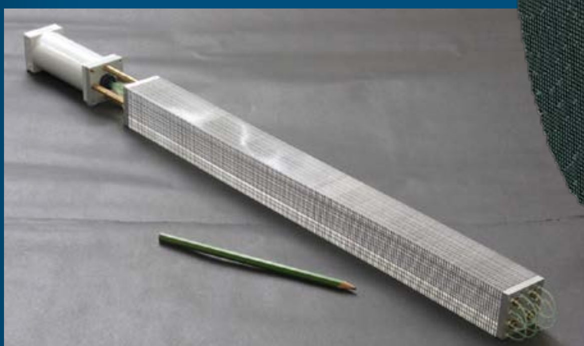
- Main challenges (< 100 ps resolution) requiring R&D
  - Long scintillating bars with large attenuation length
  - Read out by SiPM arrays
  - Embed SiPM arrays throughout scintillator along bar length to improve timing and position resolution
  - Time alignment

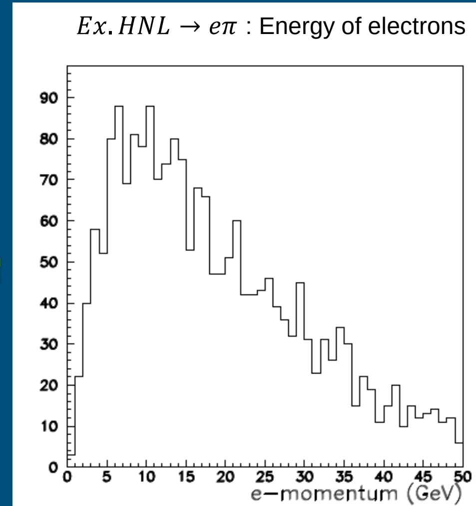
PID: ECAL/HCAL

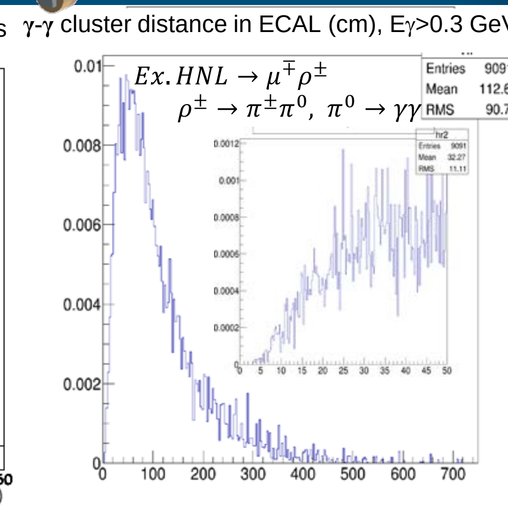


- Critical tasks
  - Identify e, γ, π^0
  - Discriminate e/π
  - Improve μ/π discrimination
- Shashlik type designs







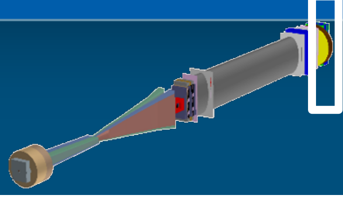


- ECAL design
  - Dimensions 6x6 cm^2
  - Radiation thickness 22.5 X_0
  - Energy resolution 5.7%/√E ⊕ 0.3%
  - Overall dimension (TP) W:5m x H:10m x D:50cm
  - ➔ 2876 modules and 11504 cells (readout channels)
- HCAL design
  - Dimensions 24x24 cm^2
  - Interaction thickness 1.7λ / 4.5λ
  - Overall dimension (TP) W:5m x H:10m
  - ➔ 1512 modules/cells (readout channels)

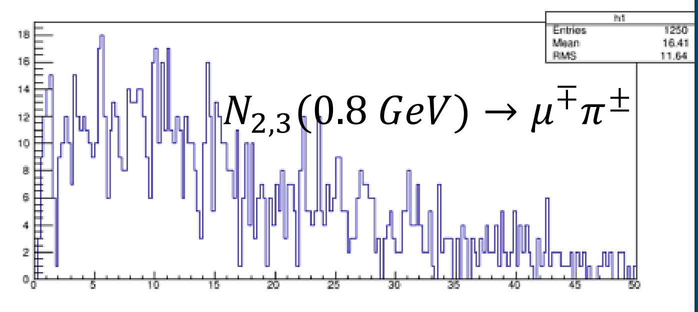
Protvino (COMPASS, SHiP): ECAL, HCAL
ITEP (LHCb, SHIP): ECAL, HCAL

- Main challenge is ECAL calibration
  - 2 x 10^9 μ /day (MIP) and 1.3 x 10^6 e /day (from μ➔e)
  - ➔ Equalization on MIP, energy scale with E/p for electrons per cell
  - ➔ $\mathcal{O}$(100) electrons/cell/day ➔ ~1% calibration accuracy in a week

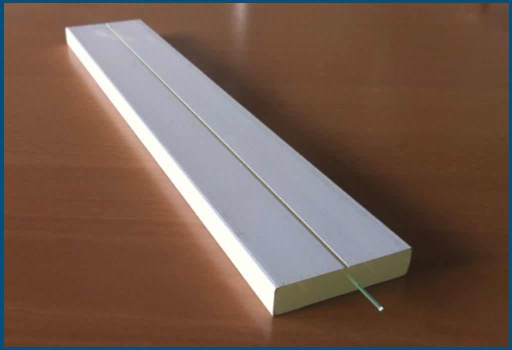
PID: MUON

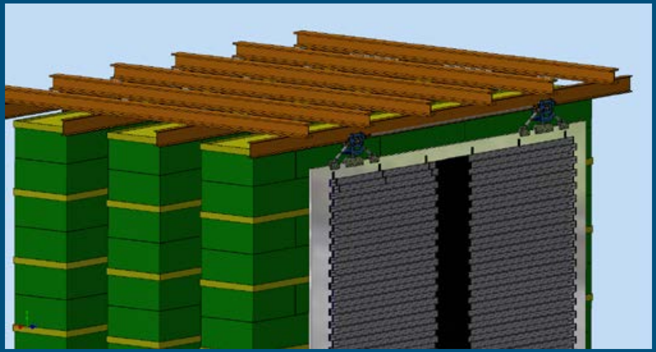


- Critical tasks: μ and π identification with high efficiency
- Challenge
  - ➔Tough as pions decay in flight before PID system
  - 20% of the pions at 2GeV, 10% at 5GeV, 4% at 30GeV



- 4 stations based on x-y plans of scintillating bars with WLS fibres and SiPM readout

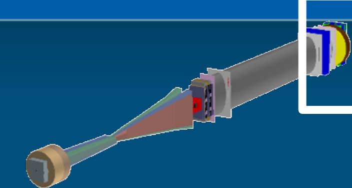


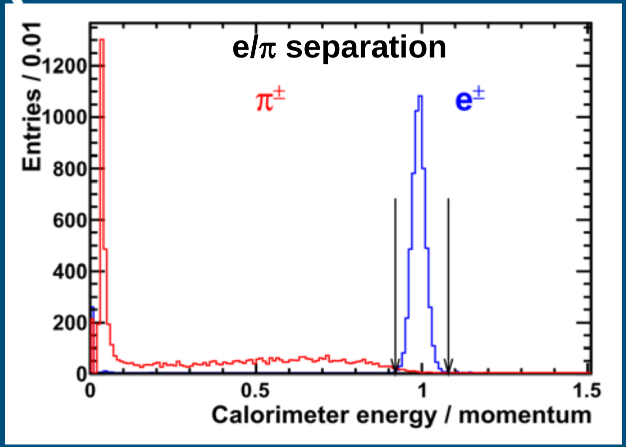


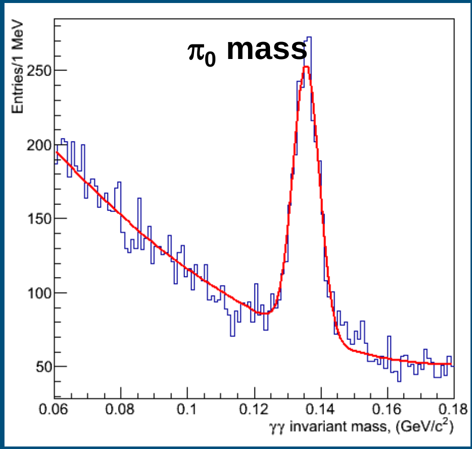
- MUON design
  - Bar dimensions — 5 x 300 x 2 cm^3
  - Number of bars — 3840
  - WLS length — 23 km
  - Overall dimension (TP) — W:6m x H:12m
  - Iron filter weight — ~1000 tonnes
  - ➔ 2876 modules and 11504 cells (readout channels)

INR (ν-physics, SHiP): MUON

PID performance







Electron efficiency >98%

Pion contamination:<2%

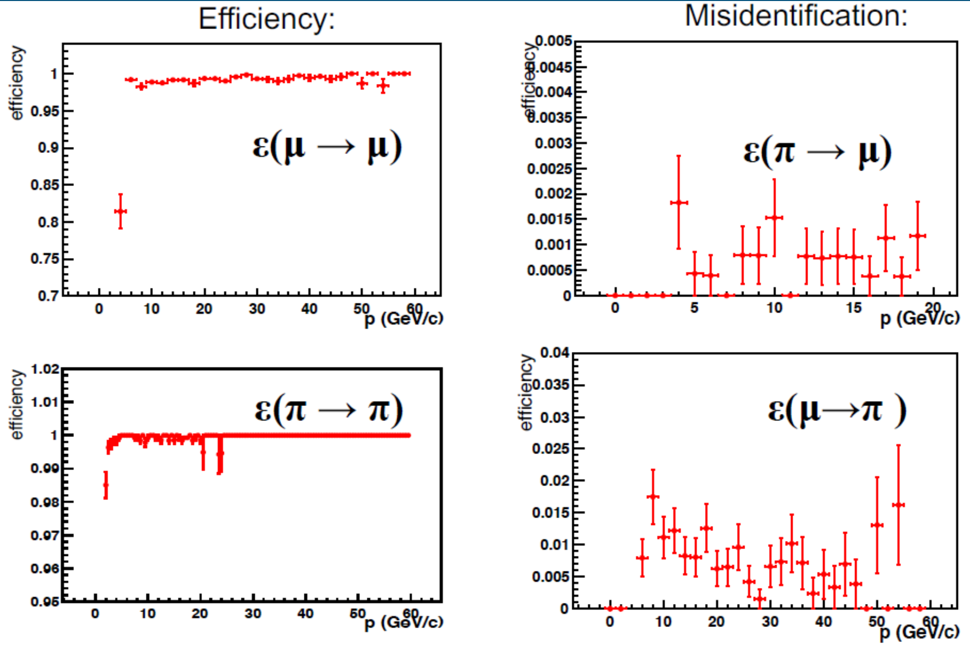
Neutral pion mass resolution: 5 MeV

Muon misid with ECAL+HCAL

Rejection factor for ε_{μ}=95%

Energy, GeV	E+H1+H2
1.0	23
1.5	32
2.0	50
2.7	120
3.0	160
5.0	210
10.0	250

2/07/2015



➔ ECAL (July), HCAL (September), MUON (October) in test beam 2015 on PS and SPS

HS signal yields

- Ex. Expected event yield $N_{2,3} \to \mu\pi$
  - Same procedure applied to all physics channels

- Expected number of signal events

$$N_{signal} = n_{pot} \times \chi(pp \to N) \times \mathcal{P}_{vtx}(\mathcal{U}^2) \times \mathcal{A}_{tot}(N \to visible)$$

  - $n_{pot} = 2 \times 10^{20}$
  - $\chi(pp \to N) = 2 \times \left[\chi(pp \to c\bar{c}) \times \mathcal{BR}(c \to N) + \chi(pp \to b\bar{b}) \times \mathcal{BR}(b \to N)\right] \times \mathcal{U}^2$
    - $\chi(pp \to c\bar{c}) \sim 1.7\text{x}10^{-3}$, $\chi(pp \to b\bar{b}) \sim 1.6\text{x}10^{-7}$
    - Integral mixing angle $\mathcal{U}^2 = \mathcal{U}_e^2 + \mathcal{U}_\mu^2 + \mathcal{U}_\tau^2$ in different scenarios of flavour coupling hierarchies
  - $\mathcal{P}_{vtx}(m, \mathcal{U}^2)$: probability that HNL decays in SHiP fiducial volume
  - $\mathcal{A}_{tot}(N \to visible)$: detector acceptance (including reconstruction) for all final states
    - $\mathcal{A}_{tot}(N \to visible) = \sum_{i=visible\ channel} \mathcal{BR}(N \to i) \times \mathcal{A}(i)$

➔ $\mathcal{P}_{vtx}(\mathcal{U}^2) \times \mathcal{A}_{tot}(N \to visible)$ based on simulation

➔ Detection efficiency entirely dominated by the geometrical acceptance

➔ Typical $\mathcal{P}_{vtx} \times \mathcal{A}_{tot} \times \varepsilon_{selection} \sim 10^{-6}$

History and Current Status

- Oct 2013: submitted our EOI: CERN-SPSC-2013-024 ; arXiv:1310.1762 ; SPSC-EOI-010
  - ➔ EOI stimulated a lot of interest
- January 2014: EOI discussed at SPSC
  - Encouraged to produce "*an extended proposal with further developed physics goals, a more detailed technical design and a stronger collaboration.*"
- January 2014: Meeting with CERN Research Director S. Bertolucci
  - ➔ Proposed a task force to evaluate feasibility and required resources at CERN within ~3months
  - ➔ Supportive to the formation of a proto-Collaboration and agreed to CERN signing
- 4 SHiP Workshops/Collaboration meetings 2014-2015
  - Explore and extend physics case
  - Preparation of Technical Proposal
  - Formalize Collaboration with >200 experimentalists and theorist from 45 institutes in 14 countries
  - Russian participation:
- Technical Proposal and Physics Proposal submitted to April SPSC